REGIONAL GEOCHEMICAL RECONNAISSANCE

INTERPRETATION OF DATA FROM THE NORTH SHORE OF LAKE SUPERIOR

P.W.B. FRISKE

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GENERAL INTRODUCTION

Geochemical data are an essential component of the comprehensive geological description of any area or country. This paper is one of a series of overviews on the geochemistry of regions of Canada.

The Geological Survey of Canada commenced regional surveys involving systematic geophysical measurements in 1949, with an aeromagnetic survey covering 30 000 km^2. By 1961 such regional geophysical surveys had expanded towards national coverage through a jointly funded Federal-Provincial program.

GSC first experimented with regional geochemical surveys in the late 1950s and continued up to the early 1970s. As a result of this work, the value of such surveys was established, methods were perfected, and the importance of sample collection and analytical controls was recognized[1]. The commencement of a large scale national program of regional geochemical surveys then waited upon the availability of funding. This opportunity arose with the energy crisis of 1973, which led to the Federal-Provincial Uranium Reconnaissance Program. This program was initiated with the support of the 1974 Annual Conference of the Provincial Ministers of Mines, and it commenced in 1975 with as expected life of 10 years. Costs for work within the provinces were shared between the Federal and Provincial governments, whilst the Federal government was wholly responsible for the cost of work in the Territories.

Between 1975 and 1979, when the Uranium Reconnaissance Program was terminated by the Federal government for economic reasons, work took place in seven provinces and all the Territories. During this period approximately 900 000 km^2 in different parts of Canada were covered by geochemical surveys. The areas covered were selected according to a variety of criteria. Work in each of the provinces was conducted through a joint Federal-Provincial management committee. Since the funds available (approximately $1.25 million per year for geochemistry) were not large in relation to the magnitude of the task, blanket coverage was not possible. Areas for geochemical surveys were selected partly on the basis of suspected exploration potential, as indicated by existing mineral occurrence and geological information, and partly to demonstrate the applicability of geochemistry in a variety of terrains.

Following on the termination of the Uranium Reconnaissance Program in 1979 most of the participating provinces indicated their interest in continuing the surveys in their areas of jurisdiction under other financial arrangements. These have varied from year to year and from province to province. They range from mostly provincial funding in British Columbia and Ontario, to wholly federal funding as in Newfoundland. Since 1979 the Geological Survey of Canada has conducted one federally funded survey

[1] These general considerations have been described by Cameron and Hornbrook (in Exploration for Uranium Ore Deposits, International Atomic Energy Agency, Vienna, 1976, p. 241-264) and Coker, Hornbrook and Cameron (in Geophysics and Geochemistry in the Search for Metallic Ores; Geological Survey of Canada, Economic Geology Report 31, 1979, p. 435-478).

INTRODUCTION GENERALE

Les données géochimiques sont essentielles à la description détaillée de la géologie de n'importe quel pays ou région. Le présent document fait partie d'une série d'aperçus sur la géochimie régionale du Canada.

La Commission géologique du Canada a commencé en 1949 à effectuer des levés régionaux, dont la cueillette systématique de données géophysiques, par un levé aéromagnétique couvrant 30 000 km^2. En 1961, ces levés géophysiques régionaux ont été étendus à tout le Canada en vertu d'un programme fédéral-provincial à frais partagés.

La CGC a exécuté ses premiers levés géochimiques régionaux à la fin des années 50 et poursuivi ses activités dans ce domaine jusqu'au début des années 70. Ces travaux ont permis d'établir la valeur de ce type de levés, de mettre au point le méthodes et de montrer l'importance de l'échantillonnage et de la vérification des résultats d'analyses[1]. La mise en oeuvre d'un vaste programme national de levés géochimiques régionaux a dû attendre que les fonds requis deviennent disponibles. L'occasion attendue s'est manifestée au moment de la crise de l'énergie en 1973, phénomène responsable de la mise sur pied du Programme fédéral-provincial de recherche pour l'uraniam. Ce programme a été lancé avec l'appui de la conférence de 1974 des Ministres provinciaux des mines, et mis en oeuvre en 1975 avec une durée prévue de dix ans. Les frais engagés dans les provinces ont été partagés entre les gouvernements fédéral et provinciaux, bien que le gouvernement fédéral ait assumé entièrement le coût des travaux exécutés dans les territoires.

Entre 1975 et 1979, lorsque le gouvernement fédéral a mis fin au Programme de recherche pour l'uranium pour des raisons économiques, des travaux avaient été exécutés dans sept provinces et les deux territoires. Au cours de cette période, une superficie d'environ 900 000 km^2 répartie dans différentes régions du Canada a fait l'objet de levés géochimiques. le régions couvertes ont été choisies en fonction de divers critères. Dans chaque province, les travaux ont été exécutés par l'entremise d'un comité de gestion fédéral-provincial. Etant donné que les fonds disponibles (environ 1,25 million de dollars par année pour la géochimie) n'étaient par considérables par rapport à l'ampleur de la tâche, une couverture complète n'a pas été possible. En ce qui concerne les levés géochimiques, les régions ont été choisies, d'une part, parce qu'elles étaient susceptibles de renfermer des gisements de minéraux, tel qu'indiqué par les venues minérales connues et les données géologiques disponibles et, d'autre part, afin de démontrer l'applicabilité de la géochimie à différents types de terrains.

En 1979, une fois terminé le Programme de recherche pour l'urnaium, la plupart des provinces qui y avaient participé se dont dites intéressées à poursuivre les levés dans les régions placées sous leur compétence, en utilisant d'autres arrangements financiers. Ces derniers ont varié d'année en année et d'une province à l'autre. Ils vont du financement provenant surtout du gouvernement provincial, comme c'est le cas en Colombie-Britannique et en Ontario, jusqu'au financement issu entièrement du gouvernement fédéral, tel

[1] *Ces considérations d'ordre général ont été décrites par Cameron et Hornbrook (dans Exploration for Uranium Ore Deposits, Agence Internationale de l'Énergie Atomique, Vienne, 1976, p. 241-264) et par Coker, Hornbrook et Cameron (dans Geophysics and Geochemistry in the Search for Metallic Ores; Geological Survey of Canada, Economic Geology Report 31, 1979, p. 435-478).*

in the Territories (Nahanni, Yukon). As far as possible, the areas surveyed have coincided with NTS sheets boundaries in order to facilitate eventual national compilations. Most of the regional geochemical survey work has been undertaken by contractors. Sample collection, sample preparation, and different types of analytical services have been performed by separate organizations. Twelve companies have taken part in these operations. The Geological Survey of Canada has been responsible throughout for overall co-ordination, compilation and checking of data. Commencing in 1976, all data (66 different sets) have been released on GSC Open File under the title of National Geochemical Reconnaissance, and this term has been commonly used in related published literature.

This paper is one of a series which has three main aims: to serve as a reminder of the extent to which geochemical reconnaissance data are available for various parts of the country; to make general comments upon the relationship between the observed surficial geochemistry and the general and economic geology of various regions; and to provide specific examples showing how these geochemical data may be interpreted. Although the prime purpose of the geochemical surveys is as a guide to mineral exploration, the same data are of value to environmentalists, and in populated areas to agriculturalists and health authorities.

Regional geochemistry is based either on the sampling of lakes, wherever they are sufficiently abundant to permit one sample to be taken every 13 km^2, or in mountainous areas on the sampling of streams, at a similar site density. In special circumstances, where additional funding has been available, more detailed sample densities have been employed. At each site both sediment and water is collected. Sediment samples have been routinely analyzed for U, Zn, Cu, Pb, Ni, Co, Mo, Ag, Mn and Fe, and loss on ignition. In some areas Ba, W, Sn, As, SB, V and Hg have also been determined. All waters have been analyzed for U, and commonly for F. From 1976 onwards pH measurements have been made on all water samples.

For the regional surveys, sample collection and sample preparation procedures, analytical methods and repeatability of results have all been tightly specified and controlled. This has been done in order to obtain consistent data between different areas, between work undertaken in successive years, and between results from different analytical laboratories. In this way the data base contributes to the eventual completion of a national geochemical reconnaissance, providing maps which have sufficient reliability to be used as an essential component of resource assessment, mineral exploration and geological mapping.

qu'à Terre-Neuve. Depuis 1979, la Commission géologique du Canada a exécuté dans les territoires (Nahanni, au Yukon) un levé financé par le gouvernement fédéral. Dans la mesure du possible, on a fait coïncider les régions à l'étude avec les feuilles de cartes du SNRC en vue de faciliter une éventuelle compilation des données pour tout le Canada. La plupart des levés géochimiques régionaux ont été exécutés par des entrepreneurs privés. Plusieurs organismes se sont chargés du prélèvement et de la préparation des échantillons, ainsi que des différents services d'analyse. Douze sociétés ont pris part à ces activités. La Commission géologique du Canada a assumé l'entière responsabilité de la coordination, de la compilation et de la vérification de tous les résultats. A partir de 1976, toutes les données (66 séries différentes) ont été publiées dans le dossier public de la CGC intitulé «National Geochemical Reconnaissance», et cette appellation a été couramment utilisée dans les publications concernant le sujet.

Le présent document fait partie d'une série qui a trois objectifs principaux: de rappeler à quel point sont disponibles, pour diverses parties du pays, les données géochimiques de reconnaissance; de présenter des commentaires d'ordre général en ce qui concerne la relation entre la géochimie de surface et la géologie générale et la géologie économique, dans diverses régions; et de fournir des exemples précis montrant comment les données géochimiques peuvent être interprétées. Bien que le but premier des levés géochimiques soit la recherche de minéraux, ils peuvent aussi servir aux environnementalistes et, dans les régions habitées, aux agronomes et aux services d'hygiène.

Les levés géochimiques régionaux sont fondés sur l'échantillonnage des lacs, là où ceux-ci sont assez nombreux pour permettre la cueillette d'un échantillon à tous les 12 km^2 ou, dans les régions montagneuses, sur l'échantillonnage des cours d'eau, à intervalles semblables. Lorsque des fonds additionnels étaient disponibles par suite de circonstances spéciales, on a utilisé un réseau d'échantillonnage aux mailles plus étroites. A chaque station d'échantillonnage, on a receuilli des sédiments et de l'eau. Les échantillons de sédiments ont été systématiquement analysés afin d'en évaluer la teneur en U, Zn, Cu, Pb, Ni, Co, Mo, Ag, Mn et Fe, et on a déterminé la perte au feu. Pour certaines régions, on a également dosé le Ba, le W, le Sn, l'As, le Sb, le V et le Hg. Tous les échantillons d'eau ont été analysés afin de déterminer la présence de l'uranium, et souvent, du fluor. A partir de 1976, on a déterminé le pH de chaque échantillon d'eau.

En ce qui concerne les levés régionaux, les méthodes de prélèvement et de préparation des échantillons, les méthodes d'analyse et la répétabilité des résultats, ont toutes été étroitement vérifiées et décrites en détail. Cette initiative avait pour but de s'assurer de l'uniformité des données provenant de différentes régions, de travaux s'échelonnant sur plusieurs années successives et de résultats d'analyses émanant de différents laboratoires. De cette façon les résultats pourront éventuellement s'incorporer à l'ensemble des données géochimiques de reconnaissance du Canada en fournissant des cartes ayant un degré de fiabilité suffisant pour être utilisées à titre d'éléments essentiels dans l'évaluation des ressources, la recherche de minéraux et la cartographie géologique.

It is not the intention of this series of overview papers to seek to identify every anomalous feature and determine its cause. This is only possible where there have been comprehensive follow-up investigations. Each of these must involve detailed field and laboratory work tailored to the problems presented by each anomaly. Only a very small percentage of the many anomalies which are present in the data have been investigated systematically by the Geological Survey of Canada or provincial agencies because of the limited human and material resources available to conduct such work. The major effort of examining anomalies has been undertaken by industry, but only in a small percentage of cases, where there have been discoveries of commercial interest, do such results become known and documented.

Different styles have been adopted in preparing the separate parts of this series of overview papers. This reflects upon the quantity of complementary information available, and other circumstances outside the control of individual authors. This series will achieve its aim if, by drawing attention to the wealth of data that are now available, it stimulates investigations that will lead to new discoveries of both scientific and economic importance.

A.G. Darnley
Director
Resource Geophysics and Geochemistry Division

Le but de cette série d'aperçus n'est pas d'identifier toutes les anomalies ni d'en déterminer la cause. Cela ne peut se faire qu'aux endroits où l'on a procédé à des études complémentaires approfondies. Chacune de ces études doit comprendre un examen détaillé sur le terrain et en laboratoire adopté à chaque anomalie. Seul un très faible pourcentage des nombreuses anomalies qui existent dans les données a été systématiquement examiné par la Commission géologique du Canada ou par des organismes provinciaux parce que les ressources humaines et matérielles disponibles pour ce genre d'activité sont restreintes. Le secteur industriel a fourni le principal effort dans la tâche d'examiner les anomalies, mais c'est seulement dans un nombre limité de cas, c'est-à-dire, à l'occasion de découvertes présentant un intérêt commercial, que ces travaux ont été publiés et documentés.

Les diverses parties de cette série d'aperçus ne présentent pas toutes le même style. Cela tient à la quantité de renseignements complémentaires disponibles et à d'autres circonstances indépendantes de la volonté des différents auteurs. Cette série atteindra son but si, en attirant l'attention sur la quantité de données qui est actuellement disponible, elle accélère la poursuite d'études susceptibles de mener à de nouvelles découvertes présentant un intérêt scientifique et économique.

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A.G. Darnley

REGIONAL GEOCHEMICAL RECONNAISSANCE: INTERPRETATION OF DATA FROM THE NORTH SHORE OF LAKE SUPERIOR

Abstract

The north shore of Lake Superior is characterized by a great diversity of Proterozoic and Archean lithologies. The Archean bedrock consists of metavolcanic-metasedimentary and paragneiss sequences, granitoid complexes and gneisses, and minor granulite terranes. Proterozoic sequences dominated by detrital sedimentary rocks unconformably overlie the Archean basement along the Superior lakeshore, near Thunder Bay, and north of Sault Ste. Marie. A large volume and variety of Helikian intrusive rocks are also present in the region.

Mineral deposits are widespread throughout the survey area, most of which are associated with Archean greenstone belts and, to a lesser extent, Proterozoic rocks. Little significant mineralization occurs in the gneissic terranes or granitoid rocks. Mineralization encountered in the area includes volcanic-associated massive sulphide deposits, Ni-Cu-Platenum Group Elements deposits, U deposits, sedimentary Fe deposits, Au deposits and, the unusual breccia-pipe deposits.

Regional trace element patterns in the lake sediments and waters are largely controlled by, and reflect, variation in the chemical composition of the underlying bedrock. Examples include the elevated levels of U associated with granitoid terranes; elevated levels of F associated with carbonatite-alkalic complexes. Scavenging by Fe, Mn and organic matter does not significantly affect the regional distribution patterns, although local variations related to scavenging are likely to occur. Other factors that may locally modify the regional distribution patterns include glacial deposits, pH of surface waters, changes in element mobility, and most notably, mineralization.

Considering the regional nature of the geochemical survey (on average one sample per 13 km^2) a relatively large number of mineral occurrences and deposits are delineated by the data; e.g., enhanced Cu and Zn levels in lake sediments of the Manitouwadge area; enhanced Cu-Mo levels in lake sediments in the vicinity of the Tribag Mine. There are also a number of anomalous zones outlined by the geochemical data that are not associated with known mineralization, indicating area of economic potential that warrant follow-up.

Résumé

La rive nord du lac Supérieur se caractérise par une grande variété de lithologies protérozoïques et archéennes. Le socle archéen se compose de séquences métavolcaniques-métasédimentaires et paragneissiques, de complexes granitoïdes et de terrains granulitiques moins importants. Des séquences protérozoïques, où les roches sédimentaires détritiques dominent, recouvrent en discordance le socle archéen le long du rivage du lac Supérieur près de Thunder Bay et au nord de Sault Sainte-Marie. La région contient également de grande quantité de roches intrusives hélikiennes variées.

Les gisements minéraux sont communs dans la région; la plupart d'entre eux sont associés aux zones de roches vertes archéennes et, dans une moindre mesure, aux roches protérozoïques. Les minéralisations importantes sont peu nombreuses dans les terrains gneissiques ou dans les roches granitoïdes. La région comporte des gisements de sulfures massifs, des gisements de nickel, de cuivre et d'éléments du groupe du platine, des gisements d'uranium, des gisements sédimentaires de fer, des gisements d'or et des cheminées minéralisées insolites.

Les schémas produits à l'échelle régionale par la répartition des éléments à l'état de traces dans les sédiments et les eaux lacustres sont en grande partie contrôlés par la variation de la composition chimique du socle sous-jacent; ils reflètent d'ailleurs cette variation. Des exemples de ces schémas sont les teneurs élevées en U associées aux terrains granitoïdes et les teneurs élevées en F associées aux complexes carbonitiques et alcalins. L'épuration par la Fe, le Mn et les matériaux organiques n'influe pas énormément sur les schémas de répartition à l'échelle régionale, mais peut donner lieu à des variations locales. D'autres facteurs sont susceptibles de modifier les schémas régionaux, y compris la présence de sédiments glaciaires, le pH des eaux de surface, les variations de la mobilité des éléments et surtout la minéralisation.

Étant donné la nature régionale de l'étude géochimique (en moyenne un échantillon par 13 km^2), les données délimitent un nombre relativement important de venues et de gisements minéraux, p. ex., les fortes teneurs en Cu et en Zn dans les sédiments lacustres de la région de Manitouwadge et les teneurs plus élevées en Cu et en Mo des sédiments lacustres près de la mine Tribag. Les données géochimiques ont également révélé la présence d'un certain nombre de zones anormales qui ne sont pas associées à une minéralisation connue; ces zones, qui pourraient se révéler économiquement importantes, méritent d'être examinées de façon plus détaillée.

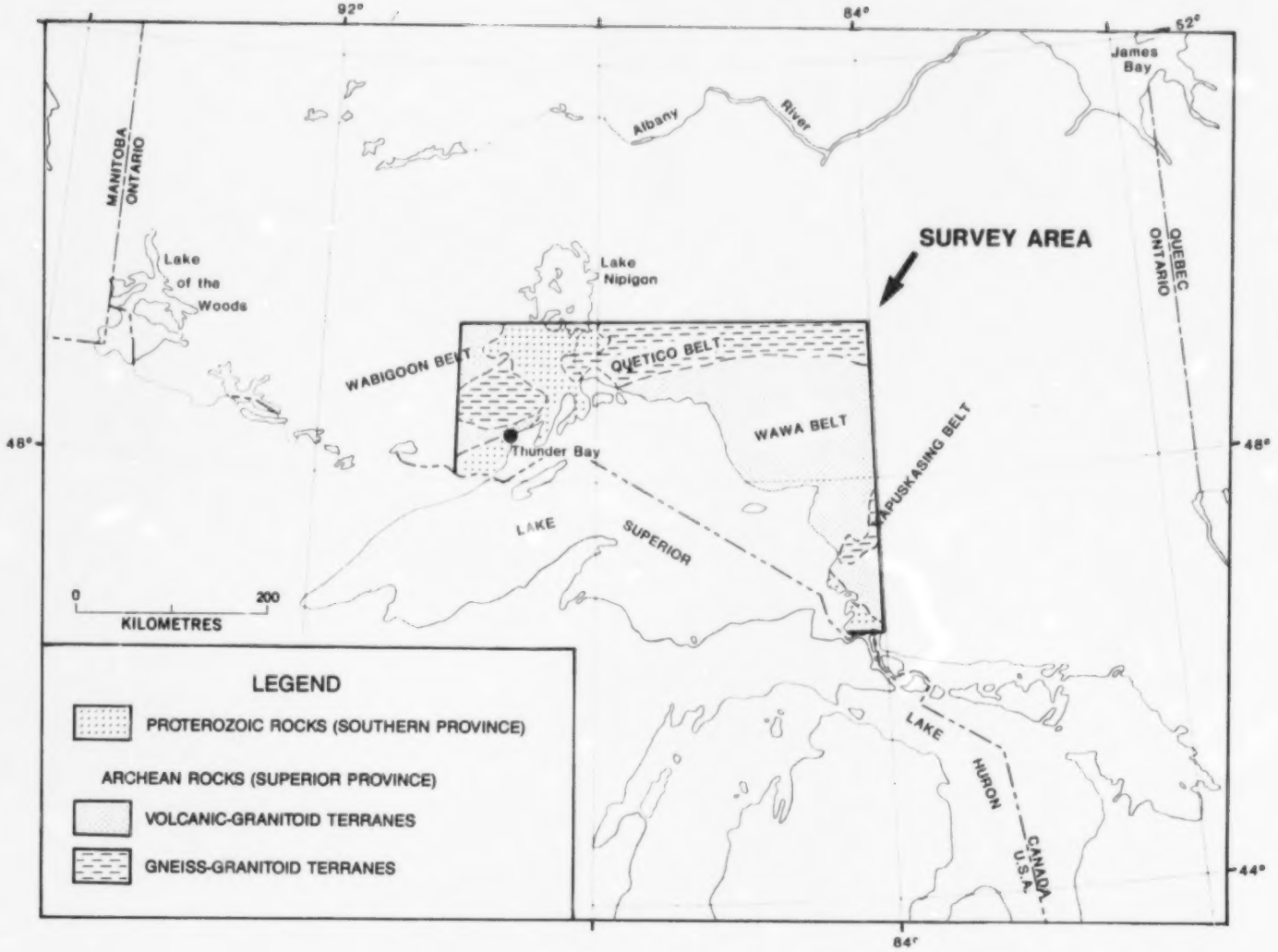


Figure 1. *Location map.*

INTRODUCTION

The Lake Superior program was a regional helicopter-supported lake sediment survey carried out during the summers of 1977 and 1978 under the auspices of the Canada-Ontario Uranium Reconnaissance Program. The data were previously published as Open Files by the Geological Survey of Canada (1978a, b; 1979a, b) and the Ontario Geological Survey (1978a, b; 1979a, b).

The survey area extends from latitude 46°30′N to 49°30′N and from longitude 84°00′W to 90°00′W (Fig. 1), covering map sheets 52A, 52H (S½), 42D, 42E (S½), 42C, 42F (S½), 41N and 41K (N½). A total of 4293 profundal centre-lake sediments and surface lake waters were collected at an average density of one sample site per 13 km². Lake sediment samples were analyzed for Cu, Pb, Zn, Co, Ni, Ag, As, Mo, Fe, Mn, LOI (loss-on-ignition), U, and Hg (Hg only on samples from map sheets 52A, 52H (S½), 42D, 42E (S½)). Lake waters were analyzed for U, F and pH.

In the Lake Superior region as in other parts of Canada, regional lake sediment and lake water data have been useful for evaluating potential in environmental studies, and as an aid to bedrock mapping. Each area, however, is unique with respect to factors (e.g., bedrock geology, mineralization, surficial geology, climate, physiography, vegetation, etc.) that control the distribution patterns of elements in the lake sediments and lake waters. As it is not possible to discuss all the observed geochemical trends, it is the objective of this report to briefly elucidate those factors important in the control of the geochemical distribution patterns in the lakes of the Lake Superior region, and to illustrate these with some examples.

Acknowledgments

The Lake Superior geochemical reconnaissance program was carried out under the direction of E.H.W. Hornbrook. Sample collection was undertaken by Marshall Macklin Monoghan Ltd. of Toronto under the supervision of E.H.W. Hornbrook and W.B. Coker. Chemical analyses were carried out by Chemex Labs Ltd. of Vancouver, Barringer Research Ltd. of Toronto and Atomic Energy of Canada Ltd. of Ottawa under the supervision of J.J. Lynch. Data monitoring and compilation was carried out by N.G. Lund. Preparation of the coloured element distribution maps was co-ordinated by W.B. Coker and D.J. Ellwood. D.J. Ellwood also prepared the computer mapping package (APPMAP) and a contouring package which facilitated data interpretation. The writer thanks J.M. Franklin, Y.T. Maurice and E.M. Cameron for reviewing the manuscript and G.E.M. Hall who is co-ordinating the series of overviews on regional geochemistry.

DESCRIPTION OF THE SURVEY AREA

Bedrock geology

The survey area is located near the southern margin of the Canadian Shield. Bedrock within this region consists of lithologies of both the Superior and Southern structural provinces (Fig. 1).

The Archean bedrock of the Superior Province is characterized by metavolcanic-metasedimentary and paragneissic sequences, granitoid complexes and gneisses, and minor granulite terranes. The distribution of these lithologies define 13 subprovinces that are generally east-trending and differ in lithology, structural style, and metamorphic grade (Stockwell et al., 1970; Goodwin, 1977; Ayres and Černý, 1982). Parts of four of these subprovinces (belts) are encountered within the survey area: Wawa and Wabigoon belts (volcanic-granitoid terranes); Quetico and Kapuskasing belts (gneiss-granitoid terranes).

Most of the survey area is underlain by rocks of low to medium metamorphic grade of the volcanic-granitoid terranes, within which granitoid rocks are aerially the most extensive lithology. In areas where supracrustal rocks (greenstone belts) do occur, metavolcanic rocks predominate, with lesser metasedimentary rocks. The metavolcanics are predominantly mafic but include intermediate and felsic volcaniclastic units. In general, the mafic metavolcanics are concentrated in the lower portions of a given volcanic sequence with intermediate to felsic rocks increasing proportionally upwards. This sequence (cycle) may occur one or more times in a particular volcanic pile. The metasediments, mainly greywacke but including conglomerate, chert, shale and iron formation (Algoma-type), are interbedded with and/or overlie the metavolcanics. Dykes, sills and plutons of mafic to felsic composition are ubiquitous, but minor, components throughout the greenstone belts.

Bedrock of the gneiss-granitoid terranes is concentrated along the northern boundary of the survey area (Quetico Belt) and north of Sault Ste. Marie (Kapuskasing Belt). Migmatitic-paragneiss of medium to high metamorphic grade is the predominant lithology in these belts but tonalitic-granodioritic orthogneiss, metasedimentary, metavolcanic and granitoid rocks are also present.

The geological history of the Archean rocks of the Superior Province is somewhat enigmatic but recent publications (Morey and Sims, 1976; Sims, 1976; Goodwin, 1977; Morey, 1978; Peterman, 1979; Ayres and Černý, 1982) indicate:

1. The volcanic belts (greenstone belts) generally range in age from 2.9 to 2.7 Ga and are generally younger than the gneisses of the gneiss-granitoid terranes.
2. The greenstone belts formed on or adjacent to pre-existing sialic protocontinents represented by the gneiss-granitoid terranes, possibly in an orogenic environment analogous to recent continental borderlands or island arcs, although there is considerable doubt as to a plate-tectonic system, as known today, operative in the Archean.
3. A large proportion of the intrusive granitoid rocks, prominent in both the volcanic-granitoid and gneiss-granitoid terranes, were emplaced during the Kenoran orogeny (2.55-2.75 Ga).

Unconformably overlying the Archean basement are Proterozoic rocks of the Southern Province that range in age from Aphebian to Hadrynian. Aphebian supracrustal sequences are exposed in the survey area along the Superior lakeshore, southwest and northeast of Thunder Bay (Animikie Group, unit 6, Fig. 2) and north of Sault Ste. Marie (Huronian Supergroup, unit 5, Fig. 2). These sequences, dominated by detrital sedimentary rocks, are part of a discontinuous linear fold belt, some 1300 km long, which developed in either intracratonic or continental-margin rift basins (Sims et al., 1981).

The Animikie Group consists of two formations: the Gunflint and the Rove. The Gunflint Formation is characterized by a local basal quartzite and conglomerate unit overlain by two cycles of taconite, chert, algal-chert carbonate rocks, and argillite-tuff that are capped by a discontinuous limestone member (Shegelski, 1982). The overlying Rove Formation consists of shale, argillite and greywacke.

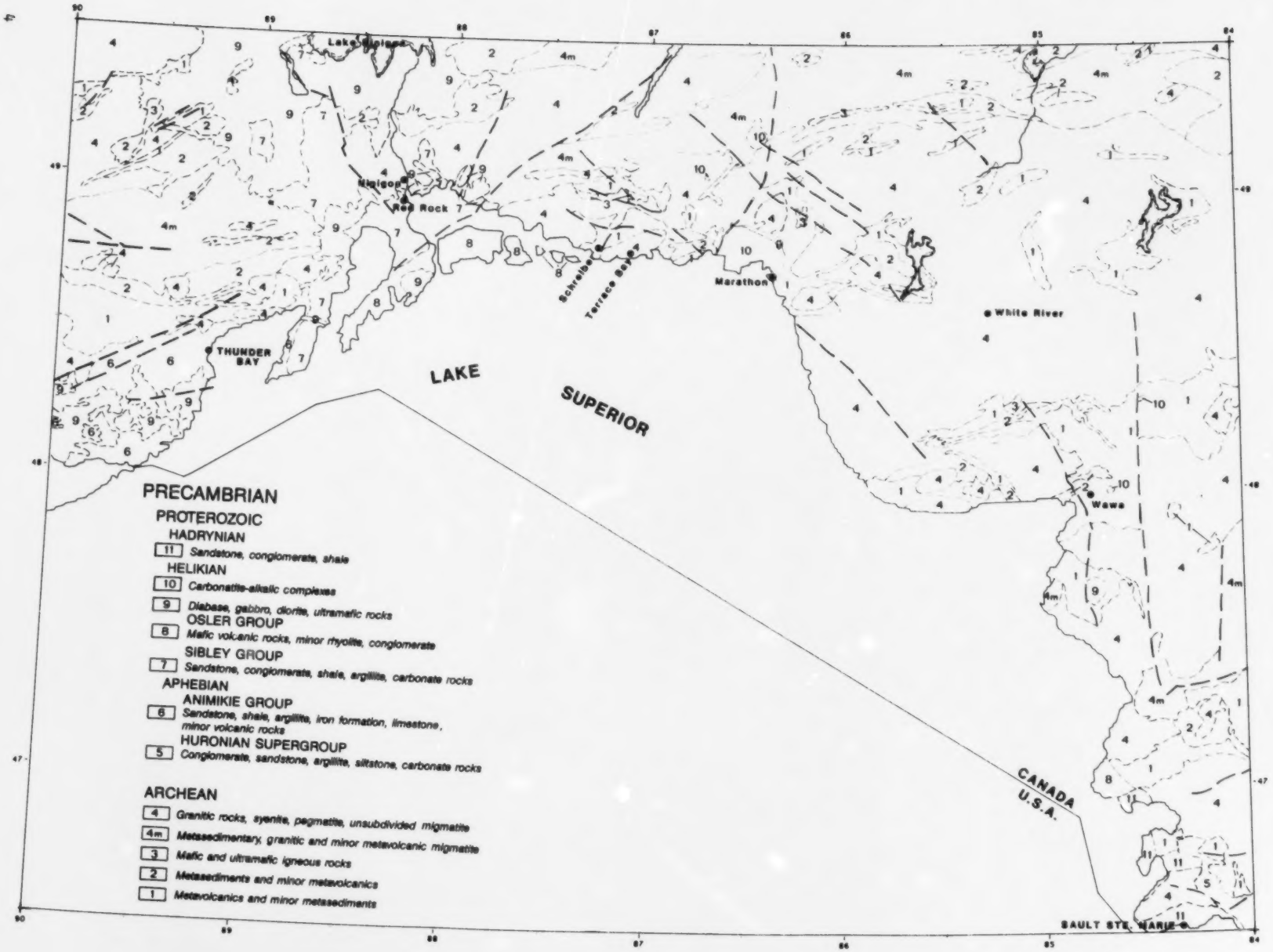


Figure 2. *Regional geology (after Ontario Geological Survey Map 2440).*

The rocks of the Huronian Supergroup, although also early Proterozoic in age, are considered to be older than the Animikie Group (Sims et al., 1981). The Huronian Supergroup is a southwestward thickening wedge dominated by clastic sedimentary rocks but includes chemical sedimentary rocks and local accumulations of volcanic rocks near its base.

The final event in the formation of Precambrian rocks in the area was the development of a continental rift system, active between about 1.4 and 0.9 Ga, that produced the Keweenawan rocks (Wallace, 1981). These Helikian to Hadrynian rocks overlie much of the Archean basement in the Nipigon area. Three lithotectonic assemblages are present. The oldest, the Sibley Group (unit 7, Fig. 2), consists of continental to marginal marine sediments that are divided into three formations (Franklin, 1978). A basal quartz arenite (Pass Lake Formation) is overlain by the Rossport Formation which consists of central chert-carbonate and stromatolite members, that are bounded by red dolomite members. The uppermost Kama Hill Formation is a sequence of purple shale, siltstone and sandstone units.

The middle Keweenawan assemblage, the Osler Group (unit 8, Fig. 2), is predominantly igneous. Subaerially deposited flood basalts predominate but intermediate and felsic flows and volcaniclastics, and interflow clastic sedimentary rocks, are also present. The upper assemblage (upper Keweenawan, unit 11, Fig. 2), exposed just north of Sault Ste. Marie, consists of clastic sedimentary rocks of fluvial, lacustrine and shallow marine origin, that were deposited as Middle Keweenawan volcanic activity waned (Wallace, 1981).

A large volume and variety of Helikian intrusive rocks (units 9 and 10, Fig. 2) are present in the area; these intrude Archean and Aphebian rocks, and Helikian supracrustal sequences. The oldest intrusions are the Logan tholeiitic diabase sills (Blackadar, 1956) which occur around Lake Nipigon and in the vicinity of Thunder Bay. Olivine diabase dyke swarms of slightly younger age are particularly common along the northeastern shore of Lake Superior. Other noteworthy Helikian intrusions include the Duluth complex, a gabbro, anorthosite and troctolite body (Phinney, 1972) that intrudes Animikie Group rocks southwest of Thunder Bay, and alkalic complexes including the Port Coldwell (Mitchell and Platt, 1977, 1982) and Killala Lake alkali syenitic bodies (Coates, 1970) and the Prairie Lake and Firesand River carbonatite complexes (Sage, 1975, 1977).

The Aphebian supracrustal rocks in the area have been only slightly deformed and metamorphosed by the Penokean Orogeny (1.90-1.80 Ga) even though this orogenic event has intensely deformed similar rocks to the south. Low grade metamorphism is also characteristic of the Keweenawan sequences and is most likely related to rapid emplacement and burial of the lava flows and sedimentary rocks (Morey, 1978).

Mineral deposits

Mineralization is widespread throughout the survey area, but the types and distribution of deposits are spatially closely related to distinct geological terranes. Much of the mineralization is associated with the Archean greenstone belts and, to a lesser extent, Proterozoic rocks. Little significant mineralization occurs in the gneissic terranes or granitoid rocks. A brief description of the major deposit types encountered in the area is given below with emphasis on their mineral and chemical compositions, which indicates possible element associations in centre-lake sediments. The locations of major occurrences and deposits are shown in Figure 3; those numbered are identified in Appendix B.

Volcanic-associated massive sulphide deposits

This type of mineralization is confined to the Archean greenstone belts, mainly associated with volcanic and volcaniclastic rocks. These deposits formed subaqueously at or near the seafloor by precipitation of metals from a hot saline brine. Mineralization is in the form of massive and stringer zones of pyrite, pyrrhotite, chalcopyrite, sphalerite, and minor galena. The deposits of this region are of the Cu-Zn type, with Pb/Zn ratios of less than 0.1 (Franklin and Thorpe, 1982). Au and Ag can be highly enriched although most massive sulphide deposits are only moderately enriched in these precious metals. Other elements commonly concentrated include As, Te, Hg, Cd, Sb and Sn. The Manitouwadge deposits (19, 20, 21) are the best examples of this type of mineralization in the survey area. Others include the Zenmac deposit (27), a raft of volcanogenic massive sulphide mineralization assimilated by a gabbroic intrusion, and the Winston Lake discovery (north of Schreiber).

Ni-Cu-platinum group elements deposits

These deposits are of magmatic origin, associated with mafic or ultramafic rocks of both Archean (e.g., Lac Des Iles (47)) and Proterozoic (e.g., Great Lakes Nickel (44)) eons. The main constituents of the mineralization are Fe, Ni, Co, Cu and S. Other elements that can be significantly enriched include platinum group elements, Ag, Au, As, Te, Se and Cr.

Uranium deposits

Several distinct types of uranium mineralization are encountered in the survey area.

1. Uranium mineralization of possible supergene origin found at the unconformity between the Sibley Group and Archean basement rocks. The U is considered to have been leached from the basement rocks and/or basal Sibley sandstone and then deposited in structural and stratigraphic traps (Franklin, 1978). An example is the quartz-pyrite-pitchblende veins of the Greenwich Lake area (33).
2. Uranium mineralization associated with carbonatite-alkalic complexes in the vicinity of Marathon (e.g., Prairie Lake prospect (31)) and Wawa (Firesand occurrence (10)). Besides U, other elements and oxides that are commonly enriched in and around these intrusions include Th, Fe, P, F, CO_2, Nb, Ba, Ti, Li, Sr, base metals and REE.
3. Uranium mineralization related to pegmatites, granitoid rocks and diabase dykes. Elevated U values are associated with pegmatites in the Greenwich Lake area and in granites, pegmatites, and the margins of diabase dykes in the Montreal River area (7). However, occurrences of this type within the survey are small and relatively unimportant.

Sedimentary iron deposits

Two types of iron formation occur: Algoma and Superior. Both are characterized by interbedded cherty and iron-rich layers. The Algoma-type (Gross, 1965) is restricted to Archean greenstone belts and, although common, is seldom economic. The mineralization at the Helen mine (11) is a carbonate-facies iron formation of this type, consisting of bedded siderite-pyrite, massive pyrite, and ferruginous chert overlying a felsic pyroclastic dome (Goodwin, 1964). The Superior-type is associated with the Aphebian sedimentary rocks of the Animikie Group, southwest of Thunder Bay. Major deposits have been found in similar rocks in Minnesota (Mesabi and Cuyuna iron ranges) but occurrences in the

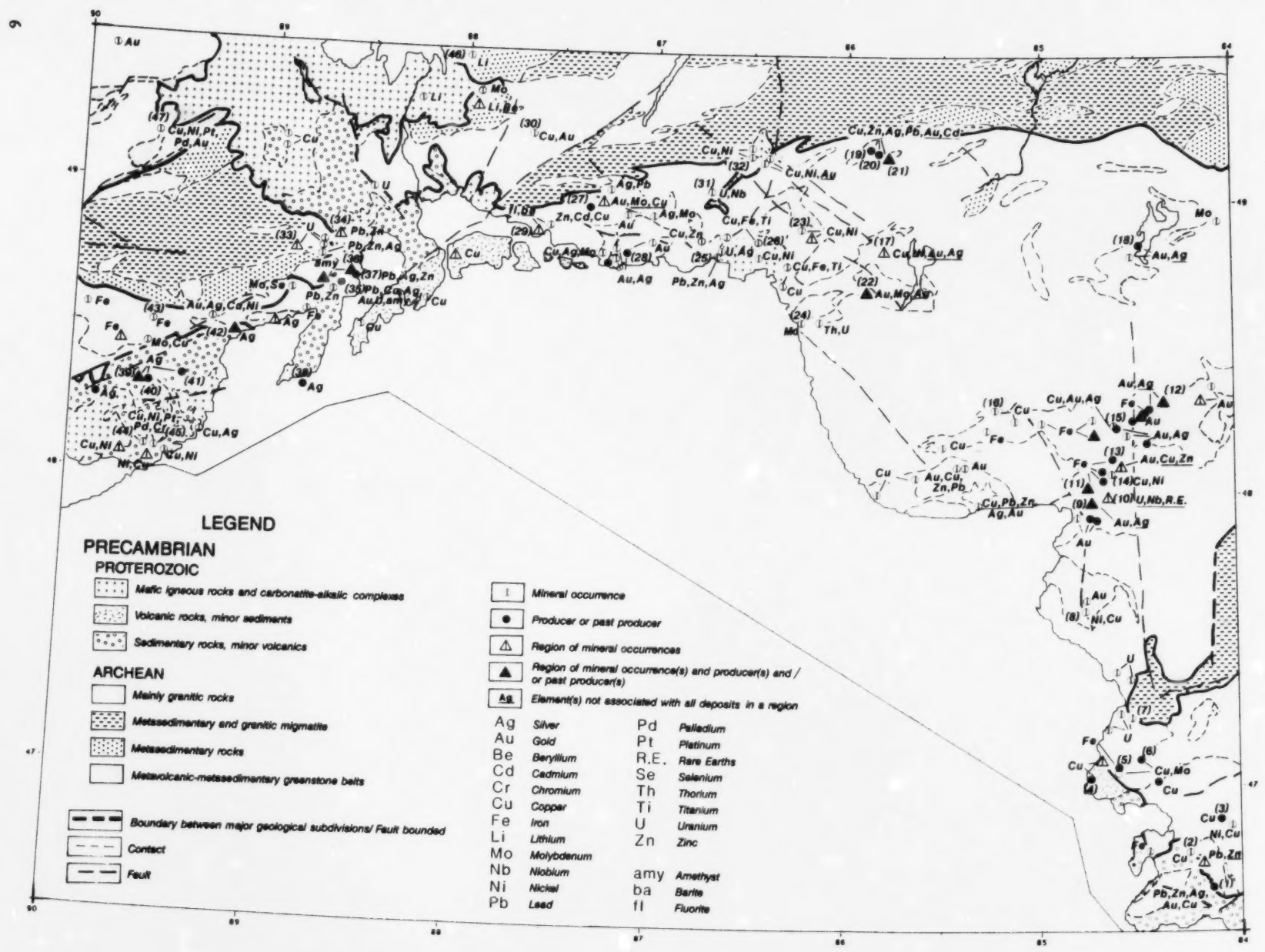


Figure 3. *General geology and distribution of selected mineral deposits (after Ontario Geological Survey Map 2310; Springer, 1977a, b, c, 1978a, b, c, d, e).*

Gunflint Formation within the survey area have not proved economic. Elements and oxides that may be significantly enriched in the various types and facies of iron formation include Fe, Mn, CO_2, As, Cu, Zn and Co.

Gold deposits

Four types of Au deposits are recognized in the Superior Province: (1) syngenetic, (2) pluton-hosted, (3) volcanic-hosted and shear zone veins, and (4) "porphyry gold" (Franklin and Thorpe, 1982). Most of the Au mineralization in the survey area is of type (3), associated with fractures, faults and shear zones within metavolcanic and metasedimentary rocks of the Archean greenstone belts. Extensive silicification and carbonatization of the host rocks is common along with enrichment of Fe, S, As, CO_2, Te, Sb, Ag, Mo and base metals (Boyle, 1979). Several Au occurrences east of Wawa are of the pluton-hosted type. The recently discovered Au mineralization in the Hemlo area (22, Fig. 3) occurs near the contact between metasediments (greywacke) and volcaniclastic tuff that are locally highly sheared and metamorphosed. Au, Mo, and Ag are the major ore elements, but there is significant enrichment of other elements, most notably, Sb, Ba, and Hg.

Vein deposits

Three general types of vein deposits other than those described above are recognized in the area. All are of Helikian age.

1. Ag and Ag-sulpharsenide veins. This mineralization is restricted to the Thunder Bay area (39, 40, 41, 42) and consists of rich ore-shoots and lenses within N60°E fault sets, that parallel the axial rift of the Lake Superior basin (Franklin and Pearson, 1982). Mineralization always occurs near diabase sills, and although usually enclosed in shales of the Rove Formation, lesser amounts occur in the Gunflint Formation, diabase sills and Archean basement rocks (Oja, 1967). Elements and oxides significantly enriched in these veins include Ag, As, Pb, Zn, Cu, CO_2, Fe, S, F and Ba.
2. Pb-Zn-Ag veins. These are fault-controlled and are spatially related to Helikian intrusions (Franklin and Pearson, 1982). This vein-type is widespread along the north and east shore of Lake Superior (e.g., 1, 25) and are enriched in Pb, Zn, Ag, Cu, CO_2, Fe, S, B and Au.
3. Pb-Zn-Ba-amythest veins. This deposit type, restricted to the Dorion region northeast of Thunder Bay, is associated with the unconformity between the Sibley Group and underlying Archean and Aphebian rocks. Mineralization is commonly coarse grained and zoned with a central galena-calcite zone, intermediate sphalerite-quartz zone, and an outermost barite-chalcopyrite zone (Franklin and Mitchell, 1977). Elements and oxides enriched include Pb, Zn, Ag, CO_2, Fe, S, Cu, Ba and F. Significant U values are encountered at the Enterprise Mine (35) but this element association is not characteristic. Franklin and Mitchell (1977) have suggested a genetic model for these veins similar to that of the aerially coincident U vein deposits described above (see U, type (1)).

Breccia-pipe deposits

Occurrences of this type are concentrated near Batchawana Bay, north of Sault Ste. Marie (e.g., Tribag (6)). Most of the breccia bodies occur near the northern margin of an Archean greenstone belt near the contact with Archean granites. Blecha (1974) has postulated that these breccias formed due to rock collapse caused by the withdrawal of a deep-seated magma, and that this igneous activity was spatially and temporally related to Keweenawan volcanism. The breccia pipes generally consist of a heterogeneous mixture of fragments set in a quartz-carbonate matrix. The fragments are of rocks found in the immediate vicinity i.e., granite, diabase, mafic volcanics and felsitic rocks. Pyrite and chalcopyrite with lesser molybdenite, scheelite, wolframite, and sphalerite occur as disseminations in both matrix and rock fragments, with local massive sulphide zones. Elements and oxides enriched include Cu, Mo, Ag, W, CO_2, Fe, S, Pb, Zn, and F.

Other types of mineralization encountered in the survey area include: Nb, U-Th, REE, Cu-Fe-Ti, and Cu-Ni mineralization related to carbonatite-alkalic complexes (10, 31, 32); Cu veins and disseminations related to Helikian strata (4); Cu and Mo mineralization in and adjacent to granitoid plutons; Li-Be-(Cb-Ta)-bearing pegmatites primarily restricted to gneiss-granitoid terranes (e.g., Georgia Lake field (46)).

Quaternary geology

The survey area has been affected by two or more periods of glaciation, but glacial features associated with the earlier events have largely been obscured by the Wisconsin glaciation that produced most of the glacial and postglacial sediments visible today. Orientation of glacial striae, drumlins and eskers indicate that the Wisconsin ice-movement was generally towards the south and southwest. Minor variations occur, notably southwest of Thunder Bay where ice-flow was towards the northwest (Fig. 4).

Till is the most aerially extensive type of glacial deposit and occurs as a discontinuous mantle over the bedrock. Generally, the composition of the till is a reflection of the composition of the local bedrock. East of Lake Nipigon, however, the till contains numerous fossiliferous limestone fragments, most likely derived from the Paleozoic limestone bedrock of the Hudson Bay Lowland. Chemical analyses have shown concentrations of up to 15 weight per cent calcium carbonate in the fine matrix of these tills (Zoltai, 1965b). Similar fossiliferous limestone fragments have not been noted in the tills west of the Nipigon moraine (Fig. 4), but tills derived from carbonate-rich sections of the Sibley Group can also contain appreciable carbonates.

As the ice-mass retreated, proglacial lakes formed in the Superior and adjoining basins and deposited varved and massive calcareous-silty-clays with lesser silt and fine sand. However, much of the area once covered by glacial lakes is either bare of glacial deposits or is overlain by till. Lacustrine deposits are concentrated along the north shore of Lake Superior, southwest of Thunder Bay, and in the northeast portion of the survey area (Fig. 4). They are most common in valleys and in low lying areas. Other less extensive types of Quaternary deposits encountered in the region include terminal moraines, eskers, outwash and eolian deposits.

Physiography, climate, vegetation, soil

Most of the survey area is characterized by broad gently rolling surfaces where relief seldom reaches 60 m. Drainage patterns are poorly developed and basins include numerous lakes, ponds and swamps, generally connected by streams. Most lakes are small (less than 10 hectares) and relatively shallow, the majority being less than 10 m deep (Cleugh and Hauser, 1971).

In areas underlain by Proterozoic rocks and along the shore of Lake Superior the terrain is more rugged. Buttes and cuestas are frequent and hills may rise as much as 275 m above the level of Lake Superior (Zoltai, 1965b). In these areas the drainage patterns are well developed and lakes and streams are not as abundant as in the flatter regions.

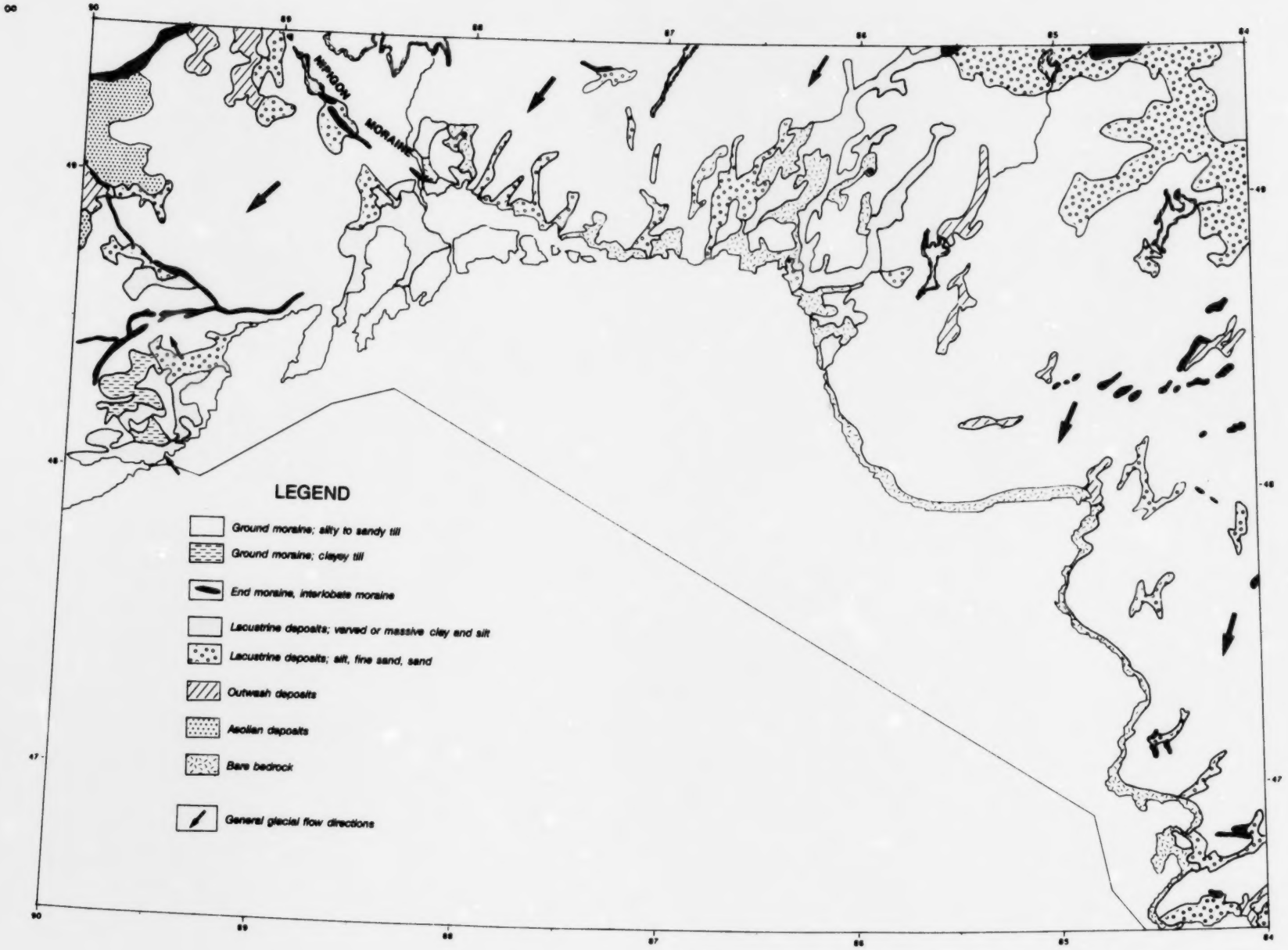


Figure 4. *Surficial geology (after Zoltai, 1965a, b).*

The climate of the area is characteristic of the Boreal zone: long and cold winters with relatively short and cool summers. The vegetation is predominantly of a Boreal forest type, coniferous with lesser deciduous trees, and locally (north of Sault Ste. Marie and southwest of Thunder Bay) a Mixed Forest type occurs. Podzolic soils are the dominant soil type encountered.

METHODOLOGY FOR LAKE SEDIMENT AND LAKE WATER SAMPLING

The lake sediment and water samples were collected by an experienced survey firm according to instructions, specifications and conditions delineated by the Geological Survey of Canada in consultation with the Ontario Geological Survey.

The area was sampled at an average density of one sample per 13 km^2. Only specified types of lakes were sampled. An ideal lake would be 1 to 5 km^2 in size, at least 3 m in depth and constitute an active part of the drainage system in a 13 km^2 grid cell. Lakes too small to be shown on a 1:250 000 scale topographic map were not sampled. Lake sediment samples were collected from the centre-lake profundal basin (shoreline sites were not accepted) using a GSC-developed, torpedo-shaped sampler attached to an external winch and rope system on the fuselage of a helicopter. With the top several centimetres of sediment from the sediment-water interface being washed out of the core barrel during retrieval of the sampler, the remaining material collected is an organic-rich sediment, commonly a greenish brown to grey thixotropic gel. Samples with a dominant sand-gravel component or totally organic peat from swampland were not acceptable. High-wet-strength paper bags, approximately 10 x 15 x 15 cm with a double fold top and water resistant glue were used to contain collected sediment samples. Lake waters were routinely collected at all lake sediment sites. These water samples were collected at least 20 cm below the surface using rectangular wide mouth linear polyethylene bottles, in water as free of suspended material as possible. To monitor and control sampling and analytical variance for both media, the basic sample design incorporated a field and blind duplicate, and a control reference sample, in every analytical block of 20 samples.

Each sampling crew consisted of a pilot, a crew member in front with the pilot who navigated, took notes and collected water samples, and a third member sitting aft who operated the winch from an outside float platform to collect the lake sediment samples. An average rate of 15 sample sites per hour was achieved while sampling on traverse. The overall survey sampling rate depended on the ferry time to and from traverses and the logistics of positioning gas caches. For detailed descriptions of sample collection and field data acquisition methods, sample preparation and analytical methods, data compilation and map production, the reader is referred to Garrett (1974), Hornbrook (1977), Coker et al. (1979), Geological Survey of Canada (1978a, b, 1979a, b, 1981), and Appendix A.

INTERPRETATION OF THE GEOCHEMICAL DISPERSION PATTERNS IN LAKE SEDIMENTS AND LAKE WATERS

General features and considerations

Virtually all elements are preferentially concentrated in certain rock types as a result of igneous or sedimentary processes, as is evident in Table 1. The geochemical distribution patterns of elements in lake sediments and waters (Fig. 5-20[1]) are to a large extent related to the variations in the chemical composition of the underlying bedrock (c.f., Hornbrook and Garrett, 1976; Jonasson, 1976; Cameron and Ballantyne, 1977; Maurice, 1977; Coker, 1979). However, other factors contribute to the development of the observed geochemical dispersion patterns, an appreciation of which is essential to fully evaluate the geochemical data. With particular reference to the survey area some of these factors are briefly discussed below.

Variation in element source

In addition to bedrock, elements can be derived from two other major sources: mineralization and surficial deposits. Although the size of a given mineral deposit is small relative to the total area of a catchment basin, it can exert a significant influence on sediment and water compositions of adjacent lakes because (1) trace elements such as Cu, Pb, Zn, Ag, Mo etc., commonly occur in mineralization in concentrations that are several orders of magnitude greater than in surrounding bedrock, and (2) mineralization usually occurs as, or is associated with, sulphides that, upon exposure, undergo rapid oxidation releasing the chemical components into the secondary environment.

Most of the area is covered by glacial deposits of which glacial till is the most widely distributed. In general, these deposits are composed predominantly of material that has been transported only a relatively short distance (Shilts, 1976), and hence the concentration of elements in the till is similar to that of the underlying bedrock. Within the region, the coincidence of distinct trace element trends in lake sediments and waters related to underlying bedrock geology (e.g., elevated Cu values coincident with the Nipigon sills (Fig. 8), elevated U values coincident with granitoid terranes (Fig. 6, 18), and elevated F values coincident with carbonatite-alkali complexes (Fig. 19)) indicates that, the regional distribution patterns for these and other elements have not been significantly displaced or obscured by the glacial till cover (pH of surface waters is an exception and is discussed below). The composition of other types of glacial deposits including lacustrine, outwash and eolian does not necessarily reflect the composition of underlying bedrock and/or mineralization. The adverse effects of transported glacial material on lake sediment surveys have been well documented by Gleeson and Hornbrook (1975), and should be considered as a possible influence on the element distribution patterns in areas covered by these deposits (Fig. 4).

Mobility of elements

"Fundamentally, the response of an element to dispersion processes is governed by its mobility, i.e., the ease with which it may be moved in any given environment." (p. 13, Hawkes and Webb, 1962). In the surficial environment dispersion processes can be broadly classified into two groups: mechanical and chemical. Within the low energy environment typical of the survey area mechanical dispersion is relatively less important than chemical (hydromorphic) dispersion in the migration of elements into the centre-lake environment (Coker et al., 1979; Cameron, 1980). Therefore the mobility of a given element in this region is largely controlled by its ability to go into true solution (i.e., free ion or soluble complex), or to form soluble colloidal complexes.

Whether a trace-metal remains in solution is controlled by the stability of the compounds it forms with other components that are in solution. Coker et al. (1979) have emphasized that in flat-lying tree-covered terrains of the southern shield, such as the survey area, the incidence of organic matter is high and metal-organic interactions are predominant. Organic matter can enhance trace-metal mobility by forming soluble or colloidal metal-organic

[1] See p. 23-38 for Fig. 5-20.

Table 1. Concentrations of selected oxides and elements in various lithologies of the survey area (north shore Lake Superior NTS 52A, 52H ($S\frac{1}{2}$), 42D and 42E ($S\frac{1}{2}$). Compiled from unpublished Geological Survey of Canada data.

Lithologic Unit (Fig. 2)	Age and General Description	Group, Formation or Lithology	N*	SiO_2 (%)	CaO (%)	Fe (%)	Mn (%)	Cu (ppm)	Ni (ppm)	As (ppm)	Co (ppm)	Pb (ppm)	Zn (ppm)	Hg (ppb)	Ag (ppm)	Mo (ppm)	F (ppm)	I (ppm)
	PROTEROZOIC																	
	Helikian																	
10	Carbonatite-alkalic complexes	Prairie Lake Carbonatite	2	1.8 0.8-1.7	42.3 41.8-42.8	0.3 0.2-0.4	0.13 0.11-0.14	1 -	1 -	0.5 -	4 2-6	1 -	12 4-8	10 -	0.1 -	4 3-4	55 -	5.2 2.1-8.2
		Coldwell Syenite Complex	8	57.1 46.8-63.9	0.2 0.1-1.1	8.5 6.1-13.5	0.16 0.09-0.25	13 3-31	15 1-75	1.8 0.3-4.2	88 6-525	31 1-117	142 1-226	13 5-19	0.1 -	15 2-18	1799 190-3700	14.2 1.0-37.5
9	Diabase, gabbro, diorite, ultramafic rocks	Diabase	5	49.6 47.8-50.7	9.8 5.0-13	10.1 7.9-12.5	0.14 0.12-0.17	58 46-66	266 42-502	2.1 0.3-2.9	229 123-361	6 1-15	123 87-177	12(4) 10-14	0.1 0.1-0.2	2 1-8	194 165-275	0.6 0.2-1.4
7	Sedimentary rocks	Sibley Group Kama Hill Formation	2	63.3 57.3-69.2	1.2 0.5-2.4	2.9 2.5-3.8	0.05 0.04-0.053	11 8-13	23 15-31	8.7 3.4-13.9	17 15-23	12 12-14	47 28-65	19 5-32	0.4 0.3-0.4	4 3-4	787 459-1115	4.8 2.9-6.6
		Rossport Formation Dolomitic members	25	51.0 23.0-95.2	13.4 6.8-32.1	1.6 0.2-3.3	0.04 0.01-0.07	5 1-9	9 3-16	2.1 0.3-7.9	12 5-34	9 1-27	22 8-32	17 5-36	0.4 0.1-5.7	3 1-6	426 85-1825	2.1 0.5-4.7
		Pass Lake Formation Sandstone member	5	86.1 78.6-94.8	2.5 0.9-7.6	0.8 0.1-2.2	0.01 0.01-0.02	3 1-10	6 1-15	0.5 0.3-1.2	25 3-79	1 -	7 3-13	24 11-41	0.2 0.1-0.5	2 1-4	130 81-205	0.7 0.4-0.9
	Aphebian																	
6	Sedimentary rocks	Animikie Group Rove Formation	2	64.2 63.9-66.4	0.1 -	3.9 3.8-4.0	0.02 0.01-0.02	10 8-12	64 48-79	2.6 2.3-2.8	32 21-43	10 1-18	134 111-147	100 65-135	0.2 -	4 3-5	1185 965-1425	3.7 3.0-6.4
		Gunflint Formation	7	73.7 41.9-96.1	3.8 0.5-7.8	5.46 0.7-10.2	0.10 0.01-0.29	14 1-42	21 1-76	12.9 3.5-35.2	46 3-124	4 1-9	19 2-56	203 44-485	0.2 0.1-0.3	8 1-17	481 41-1965	1.7 0.3-8.8
	ARCHEAN																	
4, 4m	Felsic igneous and metamorphic rocks	Granite	18	73.2 70.3-75.8	0.6 0.5-0.3	0.99 0.25-2.33	0.01 0.00-0.06	3 1-8	3 1-10	0.5 0.3-1.2	11 1-61	26 15-40	20 7-55	10 5-16	0.1 0.1-0.3	2 1-5	153 55-450	3.7 1.1-11.0
		Quartz Monzonite	19	71.3 59.9-75.5	0.1 0.0-1.5	1.3 0.3-2.9	0.02 0.01-0.12	5 1-15	5 1-25	1.6 0.1-8.5	7 1-28	26 15-85	35 14-78	56 5-429	0.1 0.1-0.3	2 1-7	274 85-1065	4.2 1.5-8.2
		Granodiorite	5	72.8 70.3-74.2	0.6 0.5-0.1	0.9 0.3-1.6	0.01 0.01-0.02	3 1-5	4 1-7	0.4 0.1-0.6	6 3-15	45 26-64	24 17-35	14 5-40	0.1 0.1-0.2	4 1-6	153 90-205	6.6 2.1-17.9
		Tonalite	1	69.7 -	0.5 -	2.0 -	0.02 -	7 -	1 -	0.6 -	5 -	25 -	56 -	15 -	0.1 -	1 -	115 -	3.5 -
		Pegmatite	13	74.9 70.6-82.9	0.5 0.0-0.1	0.7 0.1-1.5	0.04 0.00-0.29	2 1-6	4 1-13	11.6 0.2-46.9	8 1-26	28 8-69	14 7-36	11 5-19	0.1 0.1-0.2	2 1-8	116 68-205	16.9 0.7-87.8
		Granite gneiss	7	71.6 63.2-76.2	0.1 0.0-0.6	1.7 0.4-3.9	0.02 0.00-0.03	8 1-22	16 1-60	0.6 0.1-1.2	8 3-18	24 1-55	45 11-72	31 5-65	0.1 0.1-0.2	2 1-5	134 45-270	14.9 0.2-76.5
		Migmatitic metasediments	2	63.8 61.4-65.2	0.3 0.0-0.6	3.2 3.1-3.3	0.06 0.04-0.08	9 -	9 7-15	0.6 0.3-0.8	5 2-7	1 -	53 43-63	15 -	0.1 -	2 1-2	256 230-270	0.8 0.3-1.3
3	Mafic and ultramafic igneous rocks	Ultramafic rocks	2	41.3 40.2-42.4	18.6 17.5-19.6	9.6 5.3-5.5	0.28 0.23-0.32	56 48-63	3,85 340-430	122.6 109.2-134.0	45 33-46	12.5 2.5-22.5	213 98-327	15 12-18	2.2 0.1-4.3	8 3-13	193 165-220	0.1 -
2	Metasediments and metavolcanics	Metasedimentary rocks	7	64.3 61.3-68.2	0.5 0.0-0.2	4.8 3.2-6.5	0.06 0.03-0.08	25 12-25	5.5 2.8-7.6	7.7 1.2-26.6	36 8-122	14 3-29	66 29-85	19 10-49	0.1 0.1-0.2	2 1-5	224 60-400	2.3 1.5-4.0
1	Metavolcanics and metasediments	Dacite	2	65.8 64.3-67.2	1.7 0.1-3.2	2.8 2.7-2.9	0.06 -	12 -	46 2.4-59	0.2 0.1-0.2	15 9-21	7 6-7	58 57-59	26 -	0.2 -	4 3-4	185 125-245	2.9 1.0-4.3
		Basalt	1	48.3 -	9.6 -	14.6 -	0.29 -	73 -	44 -	3.8 -	143 -	1 -	138 -	70 -	0.1 -	1 -	460 -	1.5 -

N* — Number of samples
0.3(7) — Arithmetic mean (number of samples for an individual parameter that differs from the total)
0.2-0.4 — Range (minimum-maximum)

species, or retard it by the precipitation of insoluble organic complexes or sulphides. Other components in solution such as carbonate, chloride, sulphate and hydrous metal oxides can also play an important role in trace-metal migration. Moreover, local factors can significantly affect the mobility of certain elements. For example, As and Mo are strongly scavenged from solution in Fe-rich environments, either by formation of Fe compounds or by adsorption in Fe-oxides (Rose et al., 1979).

Because there is little quantitative data on the combined effects of all these factors, a quantitative estimate of the relative mobility of elements in this region is not possible. Qualitative estimates for several different surficial environments are given by Rose et al. (1979) based on coefficients of aqueous migration and practical experience. For a surficial environment similar to that commonly encountered in the region, i.e., oxidizing, pH 5-8, the order of relative mobility is given as: Mo>F≈Zn ≈Ag≈U≈As≈Hg>Mn≈Pb≈Cu≈Ni≈Co>Fe. It must be borne in mind that the order is a generalization, so that there is likely to be some variance with what actually occurs in the survey area. Moreover, the order will vary considerably in response to changes in the chemical environment. However, it serves as a general guide and illustrates the difference in the mobility of elements, which is an important consideration in evaluating any geochemical data set.

Sorbtion by hydrous Fe and Mn oxides and organic-matter

These substances have been noted for their ability to sorb (scavenge) trace elements, often resulting in anomalously high concentrations of elements that are unrelated to elevated source levels (false anomalies). Within the survey area, metal-organic interactions are of greater importance in the accumulation of trace elements in lake sediments (as opposed to hydrous iron and manganese oxides) because (1) of the characteristically high organic content in the surficial environment of the area, and (2) hydrous oxides of iron and manganese are unstable under the reducing conditions common in the profundal basins from which the centre-lake sediments were taken (Timperley and Allan, 1974; Coker et al., 1979). Sulphide precipitation may also be an important control on element accumulation but cannot be assessed with the available data.

The relation between organic content (approximated by loss on ignition (LOI), Lynch et al., 1973) and several trace elements is shown in Figure 21; two distinct trends are evident. The first, depicted by Cu and Zn (diabase) and U (granite), is characterized by a sharp increase in trace element content at low LOI values, followed by a relatively consistent trace element content over a wide range of increasing LOI, and finally a slight decrease at the upper end of the LOI scale. A similar trend between Zn and LOI in centre-lake sediments in east-central Saskatchewan was described by Garrett and Hornbrook (1976). They interpreted the relatively flat central-portion of the curve as corresponding to the range of LOI values over which there is an excess sorption capacity in the sediment, i.e., insufficient trace element available to maintain the sympathetic relation between LOI and trace element that characterizes the curve below 10% LOI. The decrease in the trace element concentration at the upper end of LOI values probably reflects a dilution effect, a disproportionally large influx of organic matter relative to trace element input.

The second trend depicted by Cu (granite) and U (diabase) is one in which there is little or no increase in trace element content with increasing LOI. This suggests

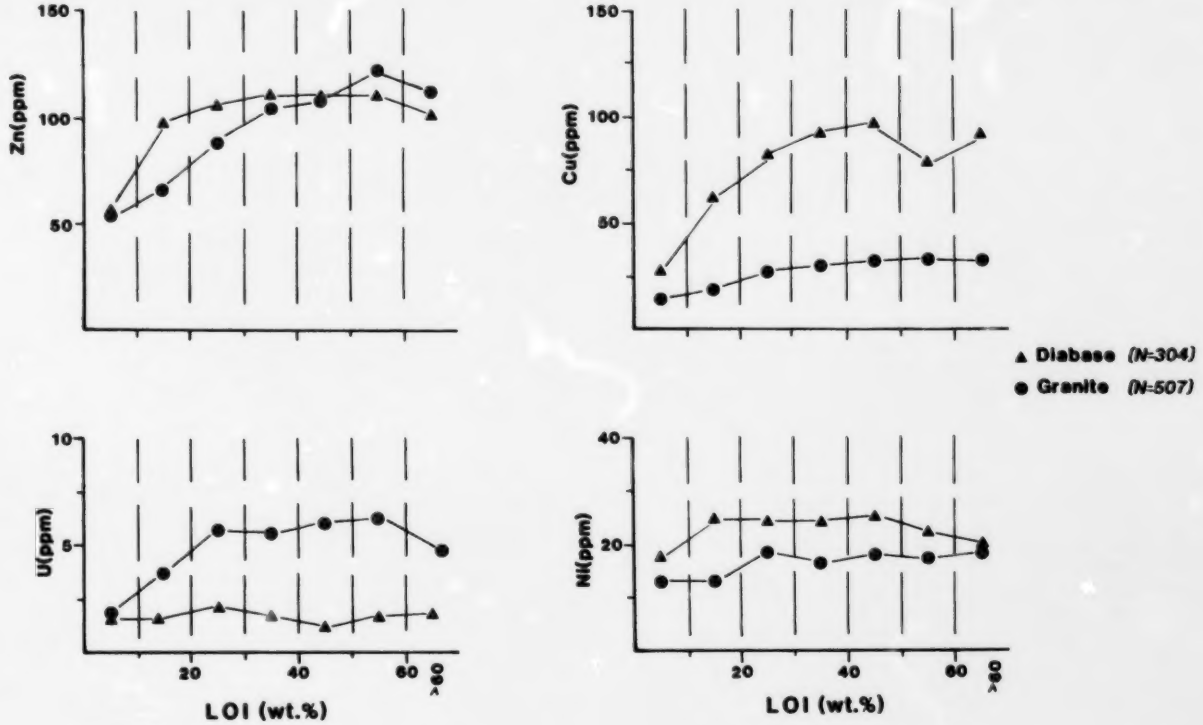


Figure 21. Variation of the U, Zn, Ni and Cu contents (geometric means) of centre-lake sediments related to loss-on-ignition and underlying bedrock type.

that there is always an excess sorption capacity in centre-lake sediments for those elements that have a relatively low concentration in solution. A similar trend would also be expected for trace elements, such as Ni, that do not have a particularly strong affinity for organic matter.

Figure 21 illustrates that the concentrations of some elements in lake sediments are not significantly affected by the content of organic matter, either because they lack a strong affinity for organic matter or because they have a relatively low concentration in solution. The accumulation of other elements that do have an affinity for organic-matter and are available in sufficient quantities will vary with LOI in a manner depicted by Cu and Zn (diabase) and U (granite). However, even for these elements, organic content will have little effect on the regional distribution patterns because most samples collected in the survey area have LOI values between 10 and 60 weight per cent and over this range there is no sympathetic increase of an element with increasing LOI (Fig. 21). Only samples with relatively low or high LOI contents need be considered as possibly anomalous, and these in terms of possibly suppressed responses. Distribution of LOI values less than 10 or greater than 60 weight per cent is shown on Figure 22d.

Distribution patterns of elements and surface water pH

pH of surface waters

The pH of surface lake waters is shown in Figure 20. In general, lakes of the Canadian Shield tend to be naturally slightly acid unless they are underlain by calcareous bedrock (Shilts, 1981). Neutral to alkaline waters are coincident with known carbonate-bearing bedrock in the survey area (e.g., carbonate members of the Sibley Group both east and west of Nipigon; calcareous units of the Animikie Group southwest of Thunder Bay; carbonatite complexes north of Marathon and east of Wawa). However, in the northeast portion of the survey area, lakes are slightly to highly alkaline (pH ranging up to 8.3), even though migmatitic-paragneiss and granitoid rocks are the dominant bedrock lithologies. The reason for this disparity is the incorporation in the till of a minor but significant amount of calcareous detritus which effects the alkaline condition when in contact with surface waters in the region. As a result of this buffering capacity of the calcareous till, the region in the northeast corner of the survey area will have an enhanced tolerance to acid precipitation, compared to most other areas of the Canadian Shield.

Coker and Shilts (1979) and Shilts (1981) have suggested that acid precipitation by its lowering of soil or surface water pH may mobilize potentially toxic substances (e.g., F, Hg, As), which are presently bound in stable forms, into streams, rivers, lakes etc. The availability of these toxic elements is obviously an important factor in the above scenario. For example, areas with naturally high concentrations of one or more of these elements are more likely to be adversely affected, other factors being equal. The variation of several elements (including F, As, and Hg) in lake sediments throughout the north shore is given below. This type of geochemical data, along with data on buffering capacity such as outlined above, can be used to help evaluate and make predictions on the effects of acid precipitation on the environment. More detailed discussions are given by Coker and Shilts (1979) and Shilts (1981).

The pH of surface waters is an important parameter in the dissolution, transport and precipitation of many elements in the surficial environment. Most metals are more soluble in acidic waters, although some, including U and Mo, are more soluble in alkaline solutions. Table 2 shows that the concentrations of most trace elements in the lake sediments and waters are not markedly affected by the relatively limited pH range of lake waters encountered in the survey area. Concentrations of Pb and Mo in lake sediments and U in lake waters show the greatest variations related to changing pH.

U in lake sediments and lake waters

Three major regionally developed zones of elevated U levels in lake sediments and waters are evident in Figures 6 and 18, and are outlined in Figure 22b (areas A, B, and C). The only known U mineralization within these zones are the pitchblende occurrences of the Montreal River area (area C'). Therefore, these regional trends are undoubtedly related to above average U content in the underlying granitoid terranes. As noted by Darnley et al. (1977), U deposits are more likely to occur associated with terranes with regionally enhanced U contents. Hence geological features in these areas, such as lineaments that could have trapped remobilized U, warrant attention.

Other zones of elevated U occur west and north of Nipigon; some reflect known U mineralization (e.g., Greenwich Lake (33)). These zones occur within the limits of the Keweenawan Sibley basin, an area considered to have a high potential for uranium deposits (Franklin, 1978). The string of anomalies to the west (area E) are less significant because they occur outside the basin and are probably related to the westward extension of the uraniferous-pegmatites which occur near the margins of the Quetico Belt and outcrop at Greenwich Lake.

As noted above, U concentrations in lake water are dependent on pH, the highest concentrations occurring in the most alkaline waters (Table 2) (c.f., Cameron and Ballantyne, 1977, Maurice, 1977). This is consistent with the findings of Cameron (1980) who showed that for lakes in northwestern Ontario there is a rapid increase in the median U content of lake waters above pH 7.5, while below this value there is no sympathetic change (the solubility of U in alkaline waters is due to its formation of complexes with carbonate). Uranium content of the organic-rich centre-lake sediments showed no variation related to changing alkalinity (c.f., Table 2). The result is that there is a significant partitioning of U between lake sediment and water that is pH-related. Cameron (1980) calculated median site ratios of U in water to U in centre-lake sediment ($Uw/Us \times 10^6$) that over the pH range of 5.0-7.4 are consistently between 7 and 10, but then rise sharply to a maximum value of over 50 at pH 8.2. This is likely an important factor in the lack of coincidence between elevated levels of U in lake sediments and waters in some of the anomalous areas outlined in Figure 22b (e.g., area C and western portion of area B).

F in lake waters

Variation in the F concentration of surface lake waters is shown in Figure 19. Most areas of elevated F levels are directly correlative with carbonatite-alkalic complexes which are characteristically enriched in F (Table 1). Examples include the Coldwell alkalic syenitic complex, the Killala Lake and the Prairie Lake carbonatite near Marathon, and several small alkalic bodies north of Wawa. Southwest of Thunder Bay elevated F contents in the lake waters are associated with sedimentary rocks of Rove Formation which has a relatively high average F content (Table 1). In this area some F may also have been derived from Helikian vein mineralization that commonly contains abundant fluorite, both within the veins and for several hundred metres into the host rocks (J.M. Franklin, personal communication, 1983). Elevated F levels in area A (Fig. 22d) reflect fluorite-bearing veins (29, Fig. 3) and granitoid rocks. Area B (Fig. 22d) which, although not associated with known mineralization, is of interest because of its multi-element association

(F, Mo, Ag, As) and coincidence with the Sibley Group which is a favourable geological environment for mineralization. Other zones of elevated F scattered throughout the survey area are likely related to fluorite-bearing mineralization or granitoid rocks, or hitherto unrecognized alkalic intrusions.

Fe, Mn, Co, and Ni in lake sediments

Elevated levels of Fe and Mn are primarily associated with areas underlain by bedrock of mafic composition which are characteristically enriched in these two elements (Table 1) (e.g., the greenstone-belts near Wawa, Schreiber and northwest corner of the survey area; mafic Helikian intrusions such as the Duluth complex, Logan sills and mafic phases of alkalic complexes; some sedimentary rocks of the Animikie Group). As hydrous oxides of Fe and Mn are known scavengers of many trace-elements, notably Co, Ni, As and Zn, it might be expected that the distribution of these elements is affected by the distribution of Fe and Mn. Although elevated levels of Co and Ni are commonly associated with areas of elevated iron and/or manganese, this association is much less pronounced over felsic terranes than mafic terranes. Moreover, the distribution of elevated Zn levels (Fig. 22e) bears little resemblance to the distribution patterns of Fe and Mn. These features support the contention (as stated in the previous section) that within the survey area Fe and Mn do not significantly affect the regional distribution patterns of trace elements in the centre-lake sediments. The occurrence of coincident elevated values of Co, Ni, Fe and Mn associated with mafic terranes is considered to primarily reflect a natural association; all four siderophile elements are enriched in mafic rocks, whereas Zn is a chalcophile element, and as described below, elevated levels to a large extent reflect sulphide mineralization.

Elevated Ni values appear to be the best indicator of Ni-Cu mineralization in the survey area which is consistent with the results of Coker and Nichol (1975). However, it is unclear as to the amount of Ni actually derived from the mineralization relative to the mafic ultramafic host rocks which are also enriched in Ni, and therefore, are potentially a major source of the Ni.

Cu, Pb, Zn, Hg, Mo, As and Ag in lake sediments

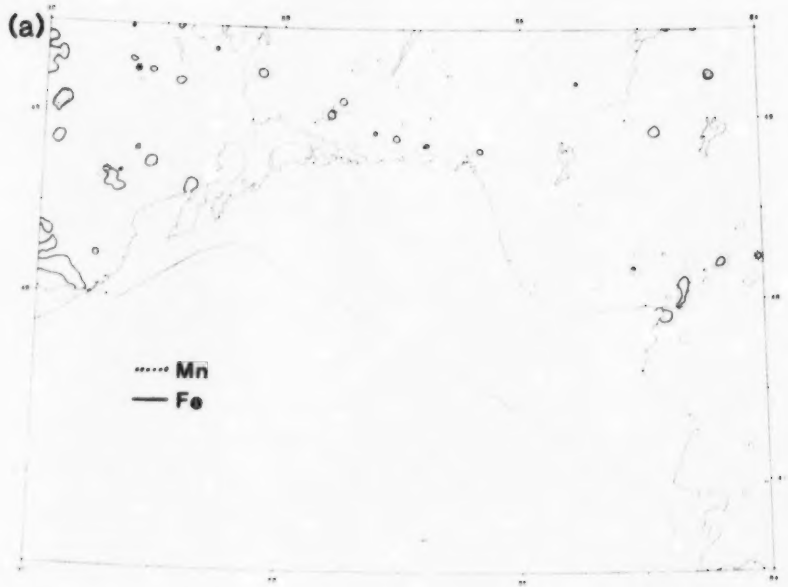
The more regionally developed trends of this suite of elements are generally related to compositional variation of bedrock; e.g., elevated levels of Zn, Hg, As (area A, Fig. 22e, f) that are aerially coincident with the Animikie Group, which is enriched in these same elements (Table 1). Other examples of elevated elemental concentrations in lake sediments attributable to enhanced bedrock concentrations include: elevated Cu values related to Helikian mafic intrusions (areas A and B, Fig. 22g); elevated As levels related to the Kama Hill Formation of the Sibley Group; elevated Hg values related to some Helikian intrusions.

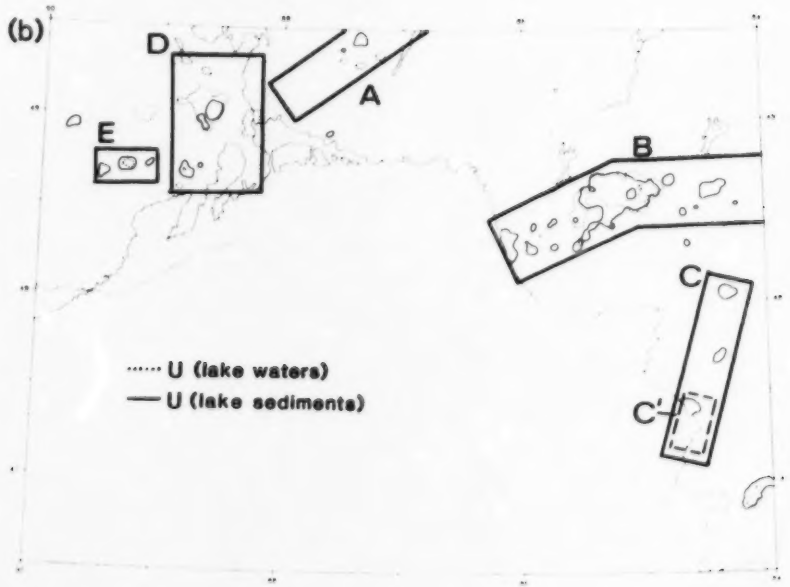
Except for Mo, this suite of trace metals are chalcophile elements and are the best indicators of sulphide mineralization within the region. There are a number of distinct single or multielement associations that are often coincident with various types of mineralization. Elevated Mo ± Cu values are commonly associated with areas of known Cu-Mo mineralization (e.g., 5, 6, Fig. 3; north of Schreiber; west of Thunder Bay) and gold mineralization, particularly northeast of Wawa. Elevated levels of Zn and Cu are coincident with the two major regions of volcanogenic sulphide mineralization, the Manitouwadge area (19, 20, 21, Fig. 3) and north of Schreiber (27, Fig. 3). It is noteworthy that there is a much more extensive Zn response over the Schreiber greenstone belt, which has a proven potential for volcanogenic massive sulphide mineralization, than the Michipicoten greenstone belt which has no significant mineral occurrences of this type. Elevated As values are found near Wawa (area B, Fig. 22f) and undoubtedly reflect the presence of the extensive Algoma-type iron formations in the area that are known to be highly enriched in As (Goodwin, 1964). Other zones of elevated As are commonly associated with greenstone belts and likely reflect similarly enriched iron formation, mafic-ultramafic bedrock, or mineralization (e.g., Au and Ag-vein deposits) enriched in As. Elevated levels in one or more of Pb, Zn, Ag and Hg are common in lake sediments coincident with areas of known Helikian polymetallic vein mineralization (e.g., west of Thunder Bay, 39, 40, 41, 42, Fig. 3; west and southwest of Nipigon, 34, 35, 36, Fig. 3; north of Sault Ste. Marie, 1, Fig. 3). The elevated levels of Zn and Hg west and southwest of Thunder Bay may in part also reflect the presence of the Animikie Group, which, as noted above, is also enriched in these elements.

Conspicuous by its absence is any lake sediment or lake water response in the Hemlo area (22, Fig. 3). The nearest sample sites are Cedar Lake, about 6 km to the east, Molson Lake, about 3 km to the south-southeast, and a small lake about 2 km to the southwest. A detailed examination of the drainage pattern in the area reveals that the Hemlo mineralization is not within one of these three catchment basins from which a centre-lake sediment was taken. Gaps in the coverage, as has happened in the Hemlo area, are unavoidable due to the regional nature of the survey (on average one sample site per 13 km^2), and must be borne in mind when interpreting the geochemical data. There can be no doubt however, that lake sediment sampling is a viable exploration technique for gold exploration in northwestern Ontario. A detailed orientation survey carried out by the GSC during the summer of 1983 determined that Moose Lake, which is just west of the Hemlo deposits, is highly anomalous in elements that are significantly enriched in the nearby mineralization, most notably Au, Sb, Mo and Hg. It is noteworthy that the base metals (Cu, Pb and Zn) and As are not enhanced in Moose Lake relative to backgound areas reflecting the absence of significant enrichment of these trace elements in the mineralization.

As in all types of geochemical surveys an important factor to be considered is the sample density. The sample density used is a function of the type and objectives of the survey modified by a knowledge of the characteristics of the elemental dispersion related to the intended target. The sample density of one site per 13 km^2 used in the regional surveys by the GSC is sufficient to satisfy the objectives of these surveys, which is largely to determine the regional distribution of elements. However, based on the initial observations of the orientation work in the Hemlo area, it is suggested that for lake sediment sampling to be used effectively in the search for gold mineralization very detailed sampling will be required. Every lake should be sampled: a single sample from relatively small lakes and multiple sampling of large lakes including samples from the centre and near each inflow.

There are a number of trace metal anomalies in the survey area that are not coincident with known mineralization. The high Pb values encountered in the northeast part of the survey area (area C, Fig. 22f) are particularly interesting. In addition to the absence of known mineralization in this area, the underlying bedrock (gneissic and granitoid rocks) are not favourable hosts to any type of mineralization in the region that contains significant Pb. A possible explanation for these anomalies is that the surficial deposits of the area contain Pb-rich detritus, derived from mineralization related to the carbonate platform to the northeast. A number of other lead anomalies occur along the east shore of Lake Superior and may reflect in part the acidic surface waters characteristic of this region; low pH tends to enhance the accumulation of lead in lake sediments (Table 2).





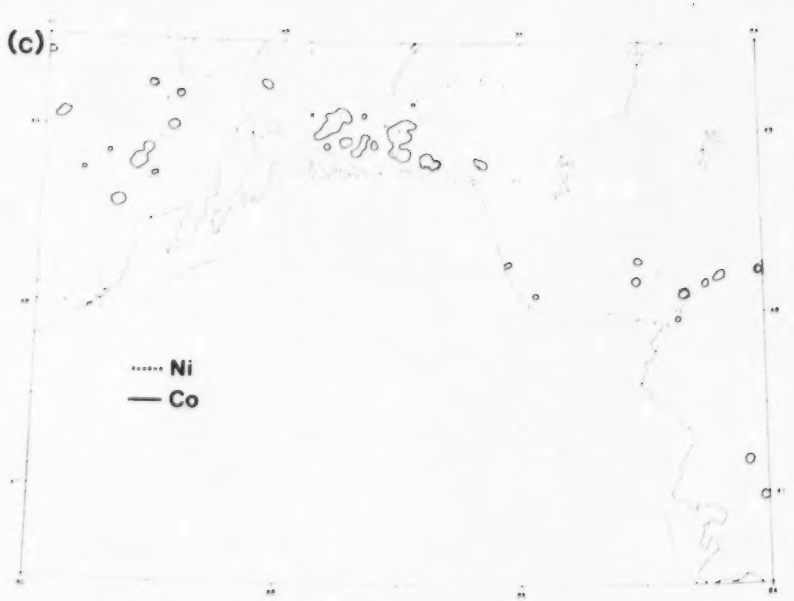


Figure 22. *Distribution of 95 percentile contours of (a) Fe and Mn in lake sediments, (b) U in lake sediments and lake waters, (c) Co and Ni in lake sediments. (d) Distribution of 10 and 60 weight per cent contours of LOI in lake sediments, and 95 percentile contour of F in lake waters. Distribution of 95 percentile contours of (e) Zn and Hg in lake sediments, (f) As, Pb and Ag (98 percentile) in lake sediments, (g) Cu and Mo in lake sediments.*

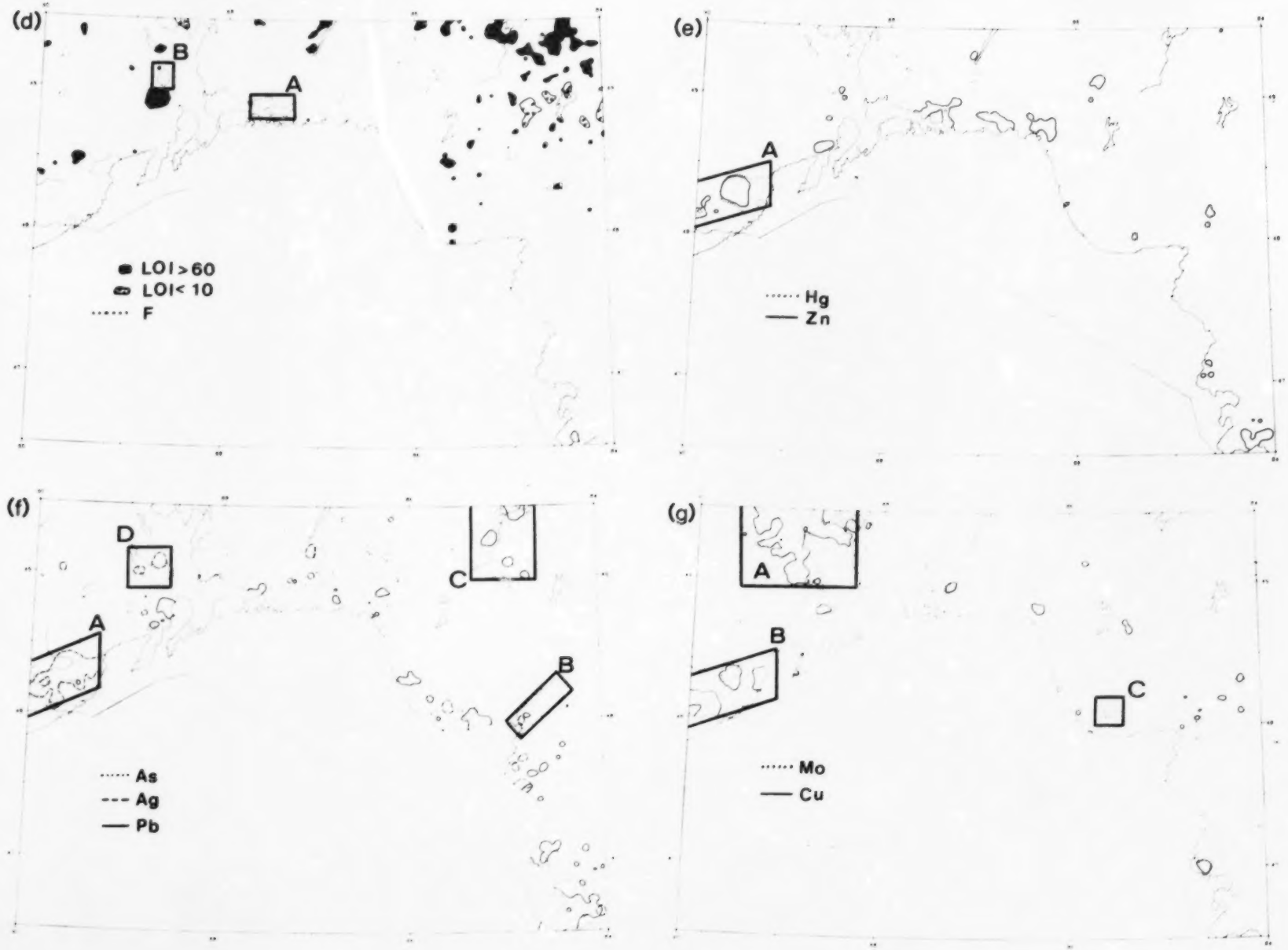

(d)
B
A
LOI > 60
LOI < 10
F
(e)
A
Hg
Zn
(f)
D
C
A
B
As
Ag
Pb
(g)
A
B
C
Mo
Cu

Table 2. Concentrations (geometric mean) of selected elements in lake sediments and waters for various levels of surface water pH. Samples are only from catchment basins underlain by granitic bedrock.

	Element	pH Intervals						
		(<6.0) (n=69)	<6.4 (n=112)	6.4-6.8 (n=140)	6.9-7.1 (n=89)	7.2-7.6 (n=111)	>7.6 (n=55)	(>8.0) (n=20)
Lake sediments	Zn (ppm)	(99)	102	118	116	104	78	(59)
	Cu (ppm)	(24)	26	34	32	31	33	(29)
	Pb (ppm)	(7.7)	7.2	5.4	4.1	3.5	3.0	(2.5)
	Ni (ppm)	(14)	15	18	18	18	17	(13)
	Co (ppm)	(6.4)	8.1	10.6	9.1	7.0	6.2	(4.5)
	Ag (ppm)	(0.10)	0.10	0.11	0.11	0.11	0.10	(0.10)
	As (ppm)	(0.54)	0.54	0.57	0.56	0.54	0.62	(0.67)
	Mo (ppm)	(1.3)	1.5	2.2	1.6	1.5	2.1	(2.8)
	Hg (ppb)	(135) (54)	138 (82)	139 (120)	122 (81)	119 (106)	103 (54)	(88)
	U (ppm)	(4.1)	4.7	5.7	6.6	5.1	3.9	(2.7)
Lake waters	U (ppb)	(0.05)	0.05	0.05	0.08	0.11	0.24	(0.27)
	F (ppb)	(56)	50	49	54	54	62	(66)

n = number of samples; for Hg, number of samples is indicated below concentration value.

There are also a number of elevated zones of Mo ± Cu (Fig. 22g) that are spatially closely related to greenstone belts. These may reflect hitherto undiscovered granitoid hosted Cu-Mo mineralization or Au mineralization of the Hemlo type which is known to be highly enriched in Mo. Area C (Fig. 22g) is particularly interesting because of the coincident zone of elevated Ag values. Area D (Fig. 22f) is a multi-element anomaly (F, Mo, Ag, As) within a favourable geological setting (Sibley Group) that warrants further investigation, particularly as an area of Helikian vein-type mineralization. These are only some examples of areas of economic potential delineated by the geochemical data.

SUMMARY

In general, the chemical composition of a lake water or lake sediment is the product of a complex system involving interplay between various physical, chemical and biological factors. Within the survey area some factors are relatively constant (e.g., climate, topography, vegetation) and hence do not contribute to the variation in element concentrations between samples. Based on available data, the factors that appear to be most important in controlling the observed chemical distribution patterns within the survey area are the distribution and chemical composition of both the bedrock lithologies and the mineralization. To a lesser extent the element variations are also a function of: pH of surface waters; sorbtion by hydrous Fe and Mn oxides, and organic-matter; changes in element mobility; and distribution and chemical composition of surficial deposits.

Although distribution and composition of bedrock lithologies and mineralization are the major factors controlling the chemical distribution patterns, most elements tend to be influenced to a greater extent by one of the two. Regionally developed trends of elevated U and F in lake waters and U in lake sediments are correlative with rock types that are enriched in these elements (i.e., U associated with granitoid rocks, F associated with carbonatite-alkalic complexes). Local highs often reflect mineralization that is also enriched in these elements. The distribution of Fe and Mn are also dominantly bedrock controlled. Elevated levels are generally coincident with areas underlain by rocks of mafic composition such as greenstone belts and mafic Helikian intrusions.

Scavenging by hydrous oxides of Fe and Mn appears to little affect the regional distribution of elements such as Co, Ni and Zn, though local enhancements are likely to occur. The common coincidence of elevated levels of Co, Ni, Fe and Mn is considered to reflect a natural association of these four siderophile elements in the same rock types. Organic-matter (concentration approximated by loss-on-ignition (LOI)) is also a strong scavenger of trace elements, but has little effect on the regional distribution patterns because most lake sediment samples collected in the survey area have LOI values between 10 and 60 weight per cent, and over this range there is no sympathetic increase of trace elements with increasing LOI. Samples with LOI levels above or below this range, however, may have suppressed trace element responses.

The distribution patterns of Mo and the chalcophile elements Cu, Pb, Zn, Ag, Hg and As are the best indicators of, and are to a significant extent controlled by, sulphide mineralization. Elevated levels of these elements in lake sediments commonly reflect mineralization that is similarly enriched in one or more of these elements (e.g., enhanced Mo ± Cu concentration related to granitoid hosted Cu-Mo mineralization; enhanced Zn ± Cu related to volcanogenic massive sulphide mineralization; enhanced As concentrations related to Algoma-type iron formation). A number of trace element anomalies also occur within favourable geological settings that are not associated with any known mineralization; these warrant further investigation. Elevated levels of these elements are also coincident with lithologies that have enhanced concentrations of one or more of these elements (e.g., Cu in mafic rocks; Hg, As and Zn in some sedimentary units of the Animikie Group).

The distribution pattern of pH in lake waters is the only variable, of those measured, that is largely controlled by a factor other than underlying bedrock composition or mineralization. In the northeast part of the survey area the surficial deposits contain a minor but significant amount of calcareous detritus, derived from carbonate rocks of the Hudson Bay Lowland. This detritus buffers the surface waters to significantly higher pH values and enhances the tolerance of this region to acid precipitation compared to other areas underlain by similar bedrock lithologies. Alkalinity of surface waters, a relative value of which can be approximated by pH, also affects the distribution of some elements (notably U in lake waters, and Pb and Mo in lake sediments) but in all cases, although it may be of local significance, it is less of an influence on the regional distribution patterns than is underlying bedrock composition or mineralization.

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APPENDIX A

Analytical Methods

Determination of Zn, Cu, Pb, Ni, Co, Ag, Mn, Fe in lake sediments

A 1 g sample is digested in 6 mL of 1M HCl - 4M HNO_3 at 90°C for 2 hours. After cooling, the solution is diluted to 20 mL with deionised water, mixed and allowed to settle. The elements are determined by atomic absorption analysis using an air-acetylene flame with background correction for Pb, Ni, Co and Ag. Detection limits are: Zn = Cu = Pb = Ni = Co = 2 ppm; Ag = 0.2 ppm; Mn = 5 ppm; Fe = 0.02%.

Determination of Mo in lake sediments

A 0.5 g sample is digested in 1.5 mL HNO_3 at 90°C for 30 minutes. 0.5 mL 12M HCl is added and the extraction continued for 90 minutes at 90°C. After cooling, 8 mL of 1250 $\mu g\ mL^{-1}$ Al solution is added, diluted to 10 mL with deionised water, mixed and allowed to settle. Mo is determined by atomic absorption using a nitrous oxide-acetylene flame. Detection limit = 2 ppm.

Determination of U in lake sediments

A 1 g sample is weighed into a polyethylene vial, capped and sealed. The irradiation is provided by a Slowpoke reactor with a flux density of 10^{12} neutrons $cm^{-2}\ s^{-1}$. The sample is pneumatically transferred from an automatic loader to the reactor where it is irradiated for 60 s. After a 10 s delay, the sample is counted for 60 s with 6 BF_3 detector tubes embedded in parrafin. Calibration is carried out twice daily used natural materials of known U concentration as standards. Detection limit = 0.2 ppm.

Determination of Hg in lake sediments

A 0.5 g sample is digested with 20 mL 16 M HNO_3 and 1 mL 12M HCl for 10 minutes followed by 2 hours at 90°C. After cooling, the sample solution is diluted to 100 mL with deionised water, mixed and allowed to settle. Hg vapour is formed by the addition of 10% (w/V) $SnSO_4$ in 1M H_2SO_4 and is flushed into a cell in the light path of an atomic absorption spectrophotometer where measurement is made at 253.7 nm. Detection limit = 10 ppb.

Determination of As in lake sediments

A 0.25 g sample is leached with 10 mL of aqua regia at room temperature for 2 hours and then heated to 90°C for a further 2 hours. After cooling, a 1.0 mL aliquot is taken and diluted to 10.0 mL with 0.5 M HCl in a test tube. Arsine is generated by the addition of 2% (w/V) sodium borohydride and the gas swept into a silica tube heated to 850°C in the light path of an atomic absorption spectrophotometer. Measurement is made at 193.7 nm against known standards. N.B. The values obtained by this method are sometimes higher than those obtained by the colorimetric method (used in earlier surveys), depending upon sample type. Detection limit = 1 ppm.

Determination of LOI in lake sediments

A 0.5 g sample is weighed into a beaker, placed in a cold muffle furnace and the temperature raised to 500°C over a 2-3 hour period. The sample is maintained at 500°C for 4 hours, cooled and reweighed. Detection limit = 1.0%.

Determination of F in lake waters

An aliquot of the water sample is taken and an equal volume of TISAB (total ionic strength adjustment buffer) is added. The mV reading is measured with an ion-selective electrode combined with a reference electrode and the F concentration found from a calibration graph constructed with known standards. Detection limit = 20 ppb.

Determination of U in lake waters

After collection, the water sample (≈225 mL) is acidified with 3 mL 12 M HNO_3 Two weeks later, a 5≈L aliquot is removed and spotted on a polycarbonate tape. The tape is irradiated for 1 hour with a flux density of 10^{13} neutrons $cm^{-2}\ s^{-1}$. The tape is then etched with 25% NaOH solution and the fission tracks counted with an optical counter fitted to a microscope. Calibration standards are subjected to the same procedure. Detection limit = 0.01 ppb.

Determination of pH

The hydrogen ion activity is measured with a combination pH electrode and a specific ion meter which has been calibrated with standard solutions at pH 4.00 and 7.00.

APPENDIX B

Listing of Selected Mineral Deposits

Deposit or region Reference number (Fig. 3)	Deposit	Commodities	Status*
1	Jardun mine (Cascade and Victoria	Pb, Zn, Ag, Au, Cu	2
2	Eagle (Edwards) mine	Cu	3
3	Kristina (Supercrest) mine	Cu	2
4	Coppercorp Mine (North Canadian Enterprises Ltd.)	Cu	2
5	Batchawana Iron Co. Ltd.	Fe	2
6	Tribag Mining Co. Ltd.	Cu, Mo, W	2
7	MONTREAL RIVER AREA Labine-McCarthy occurrence	U	3
8	Renner occurrence (Teck Group Ltd.)	Ni, Cu	3
9	(a) Pursides Gold Mines Ltd. (Surhiga, Jubillee, Copper, Minto mines)	Au	2
	(b) Darwin (Grace) mine (Denison Mines Ltd.)	Au	2
	(c) Deep Lake mine	Au, Ag	2
	(d) Parkhill, Smith mines	Au	2
10	Firesand occurrence	Nb	3
11	MacLeod mine (Algoma Steel Corp. Ltd.)	Fe	1
12	Cline Lake mine (Pick Mines Ltd.)	Au	2
13	Josephine mine (Michipicoten Iron Mines Ltd.)	Fe	2
14	Lakemount Mines Ltd.	Cu, Ni	3
15	Ego Mines Ltd.	Cu, Au, Ag	3
16	Heart Lake prospect	Cu	3
17	Pulfa prospect	Cu, Ni, Au, Ag	3
18	Hiawatha gold mine (Hollinger Mines Ltd.)	Au	2
19	Willecho mine	Cu, Zn, Ag, Pb, Au	2
20	Big Nama Creek Mines Ltd.	Cu, Zn, Ag, Pb	2
21	(a) Geco mine (Noranda Mines Ltd.)	Cu, Zn, Ag, Au, Pb, Cd	1
	(b) Willroy mine	Zn, Cu, Ag, Pb, Au	2

* 1 – Producer; 2 – Past producer; 3 – Occurrence

Appendix B (cont'd)

Deposit or region Reference number (Fig. 3)	Deposit	Commodities	Status
22	HEMLO AREA		
	(a) Golden Giant (Noranda Mines Ltd.)	Au, Mo	1**
	(b) Teck-Corona prospect	Au, Mo	1**
	(c) Williams Deposit (Lac Minerals)	Au, Mo	1**
23	Beggs-Currie (Pic Nickel) prospect	Cu, Ni	3
24	Playter Bay occurrence	Mo	3
25	Hannem prospect	Pb, Zn, Ag	3
26	Lakehead Mines Ltd.	Cu, Fe, Ti	3
27	Zenmac Metal Mines Ltd.	Zn, Cd, Cu	2
28	Harkness-Hays mine	Au, Ag	2
29	Halonen, J. occurrence	fl, ba	3
30	Kabamichigama prospect	Cu	3
31	Prairie Lake prospect (New Insco Mines)	U, Nb	3
32	Killala Lake prospect	Cu, Ni	3
33	GREENWICH LAKE AREA		
	Christianson showing	U	3
34	(a) Bishop prospect	Pb, Zn, Ba	2
	(b) Dorion mine	Pb, Zn, Ba	2
	(c) Thunder Bay prospect	Pb, Zn, Ba	2
35	Enterprise mine	Pb, Cu, U	2
36	Ontario Gem Company	amythest	1
37	Caribou mine	Pb, Zn	2
38	Silver Islet mine	Ag, As, Ni	2
39	(a) Badger (McWilliams) mine	Ag	2
	(b) Beaver mine (Cairngorm Mines Ltd.)	Ag	2
	(c) Porcupine mine (Climax Silver Mines Ltd.)	Ag	2
40	Rabbit Mountain mine	Ag	2
41	Algoma mine	Ag	2
42	(a) Shuniah (Duncan) mine	Ag	2
	(b) Thunder Bay mine	Ag	2
43	Kaministikwia prospect (Inland Steel Co. Ltd.)	Fe	3
44	Great Lakes Nickel Ltd.	Cu, Ni, PGE	3
45	Thunder Bay Nickel prospect	Cu, Ni, PGE, Cr	3
46	Big Nama Creek Mines Ltd.	Li	3
47	Lac des Iles prospect	PGE, Cu, Ni	3

** Production to begin in 1985

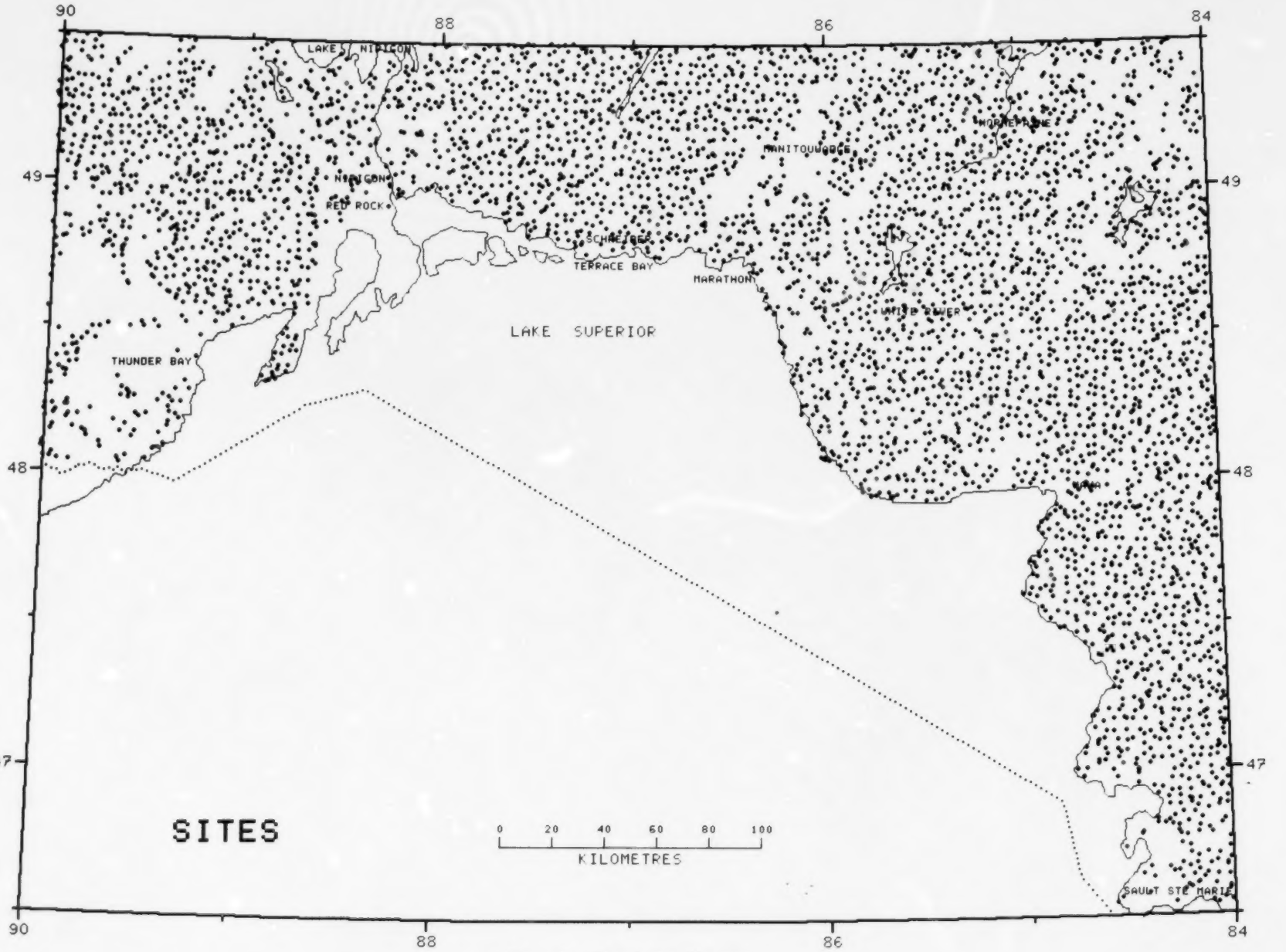

Figure 5. Sample location map.

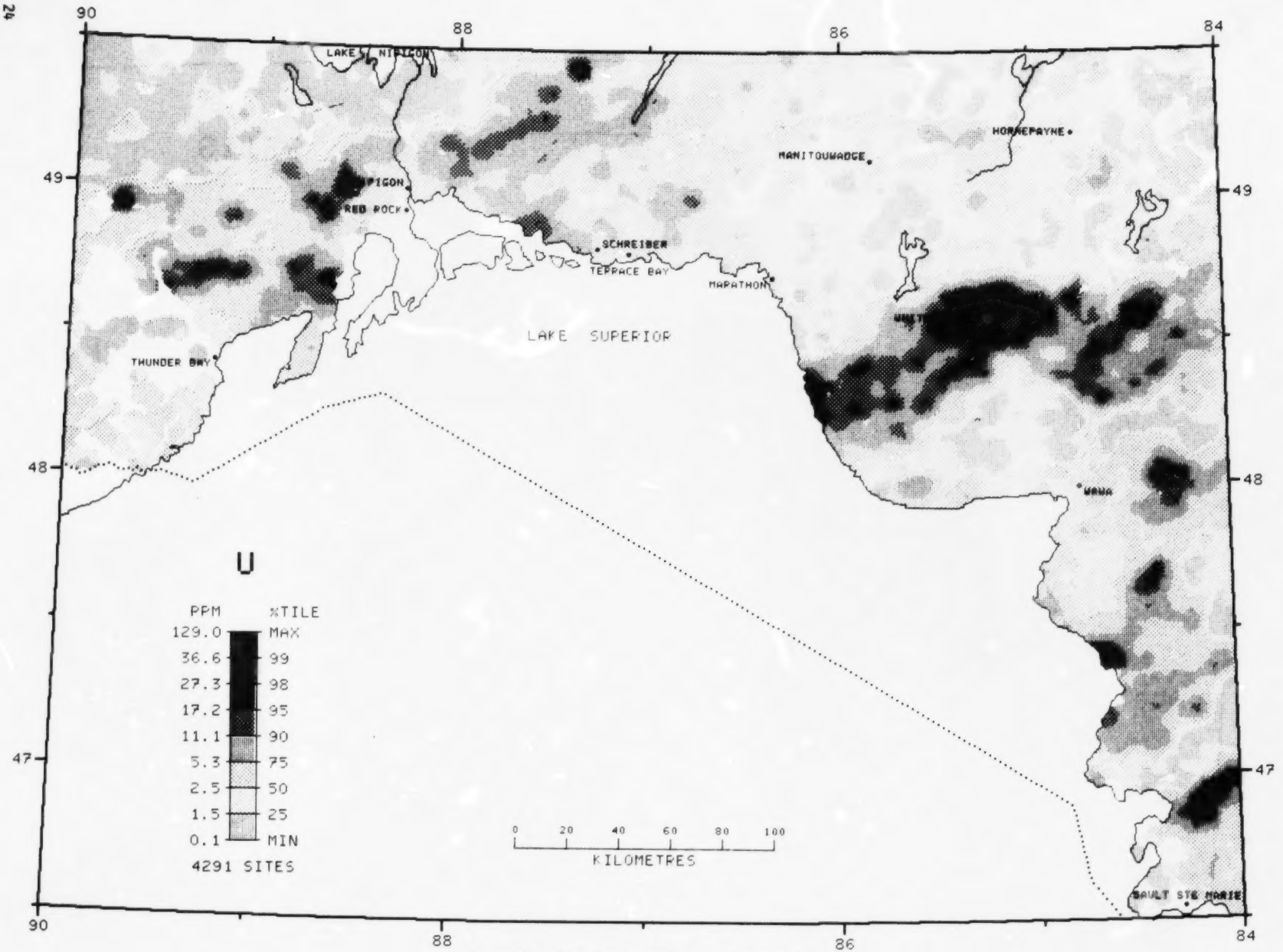

Figure 6. *Distribution of U in lake sediments.*

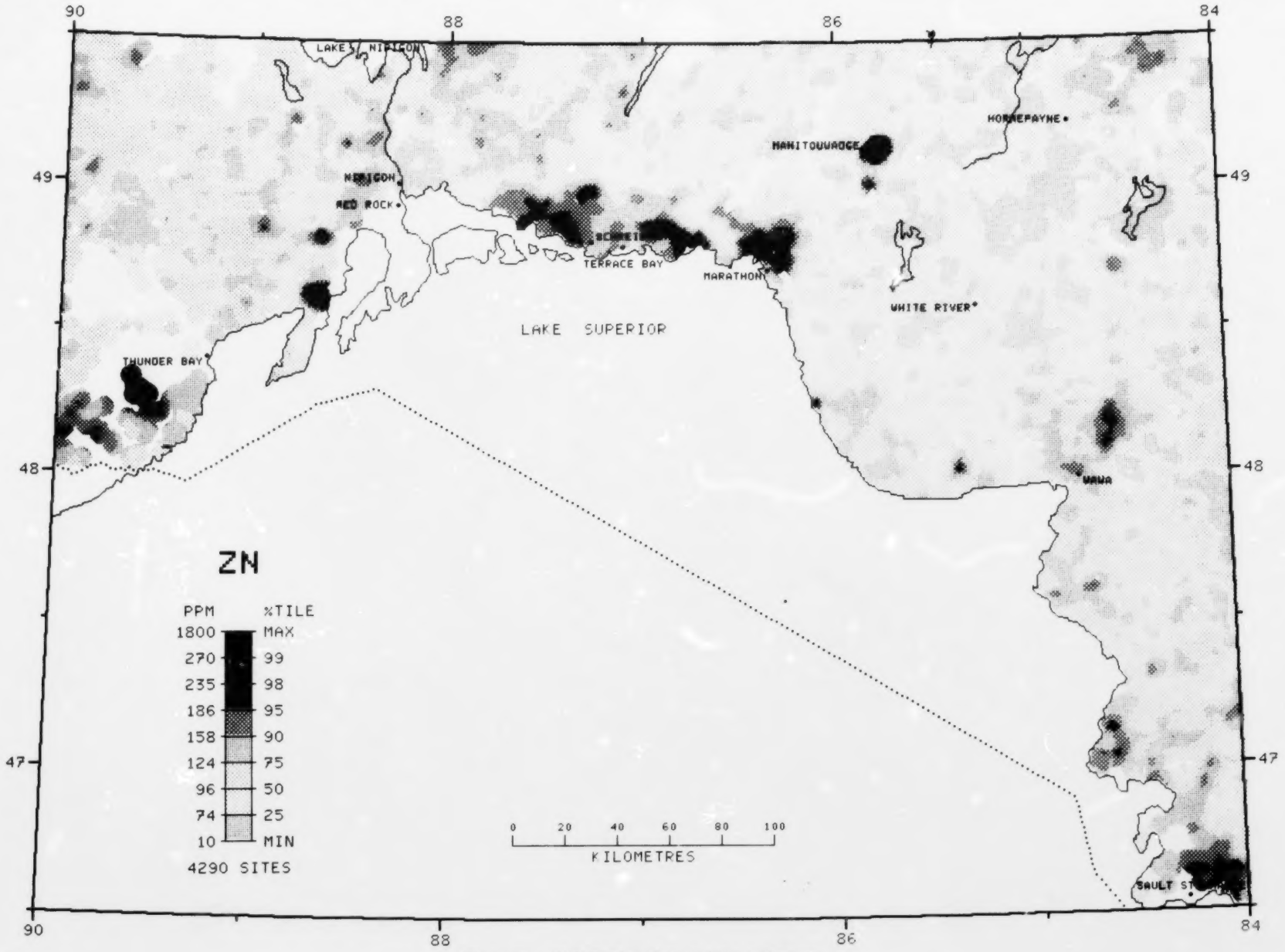

Figure 7. *Distribution of Zn in lake sediments.*

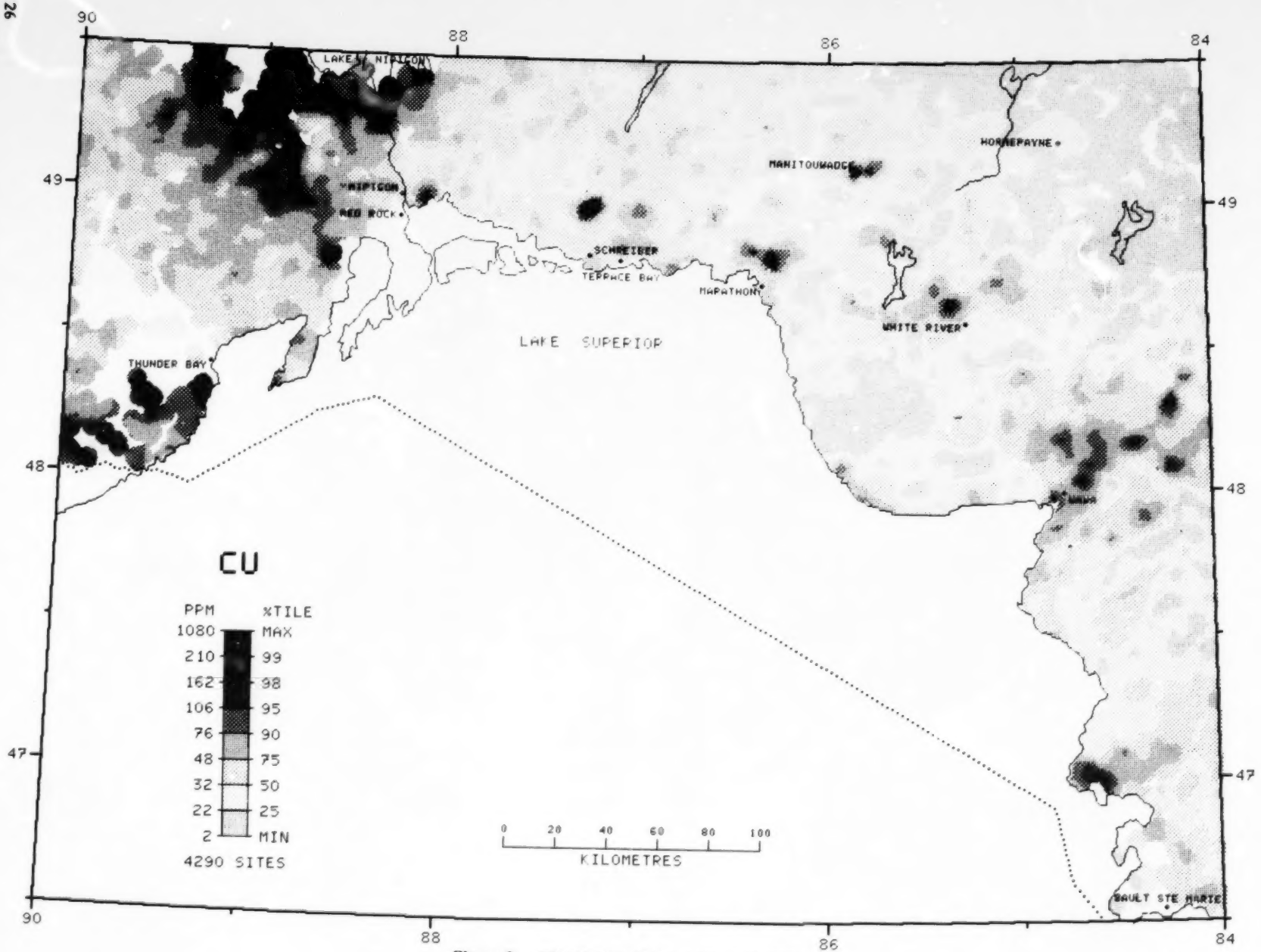

Figure 8. *Distribution of Cu in lake sediments.*

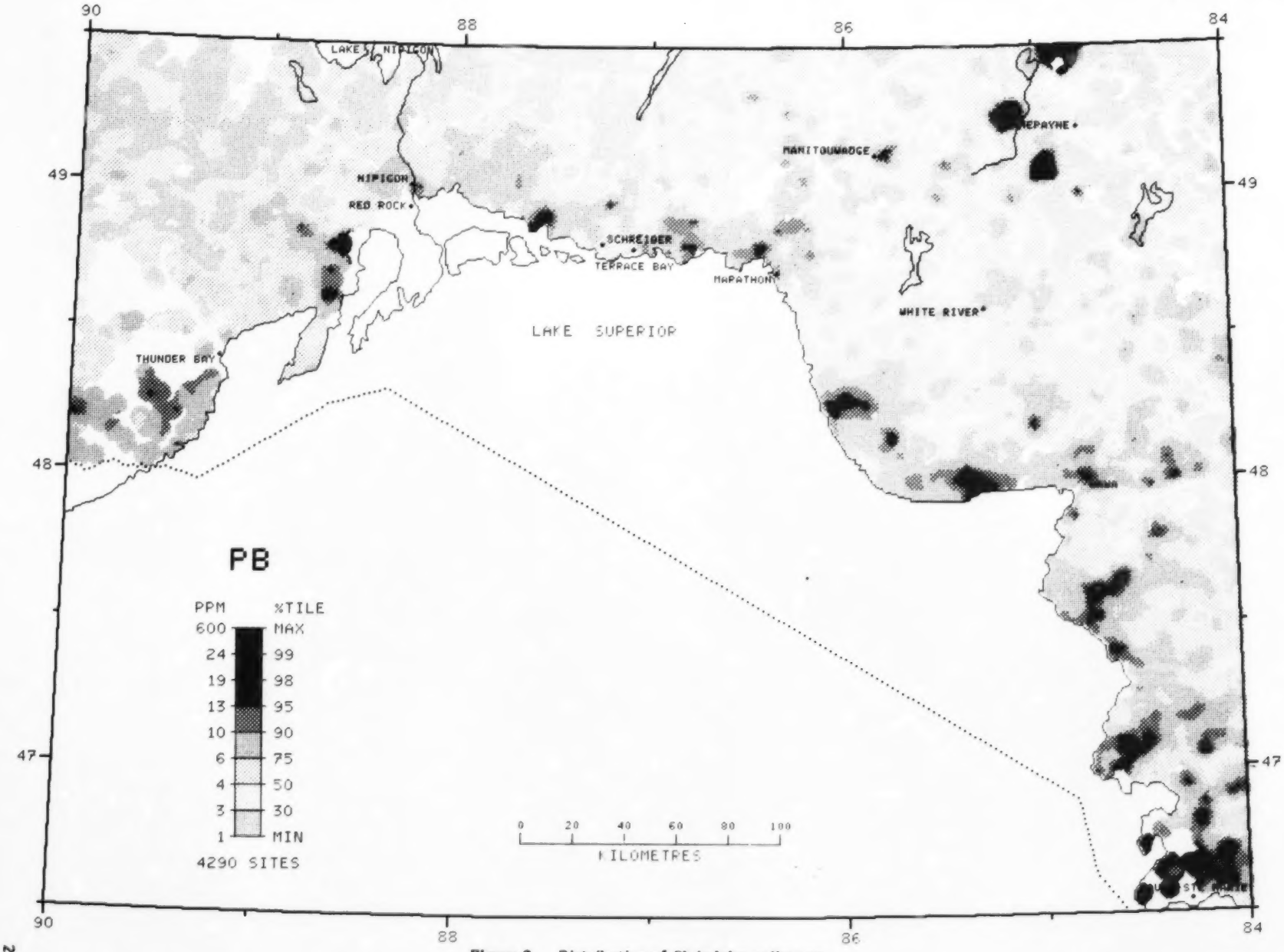

Figure 9. *Distribution of Pb in lake sediments.*

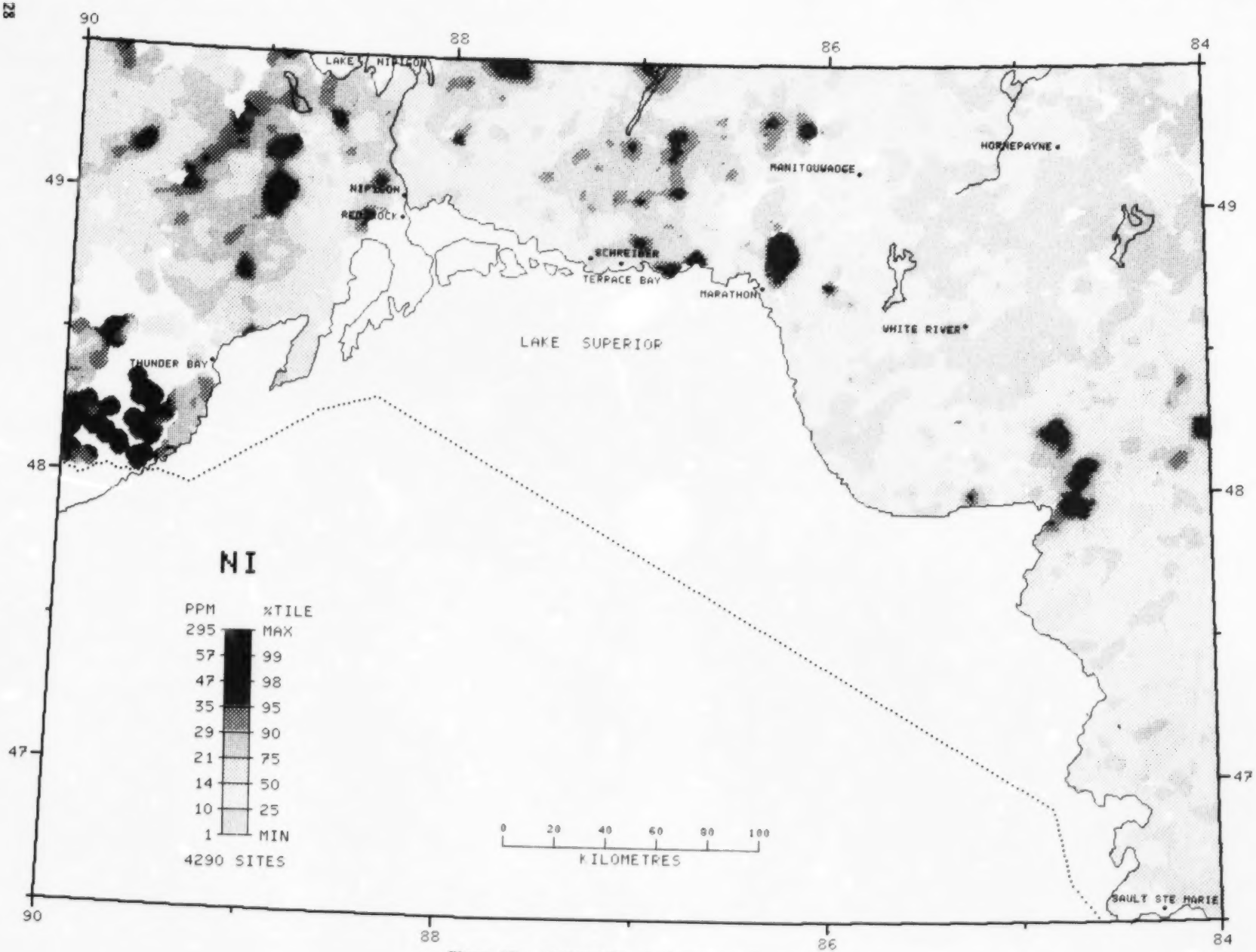

Figure 10. *Distribution of Ni in lake sediments.*

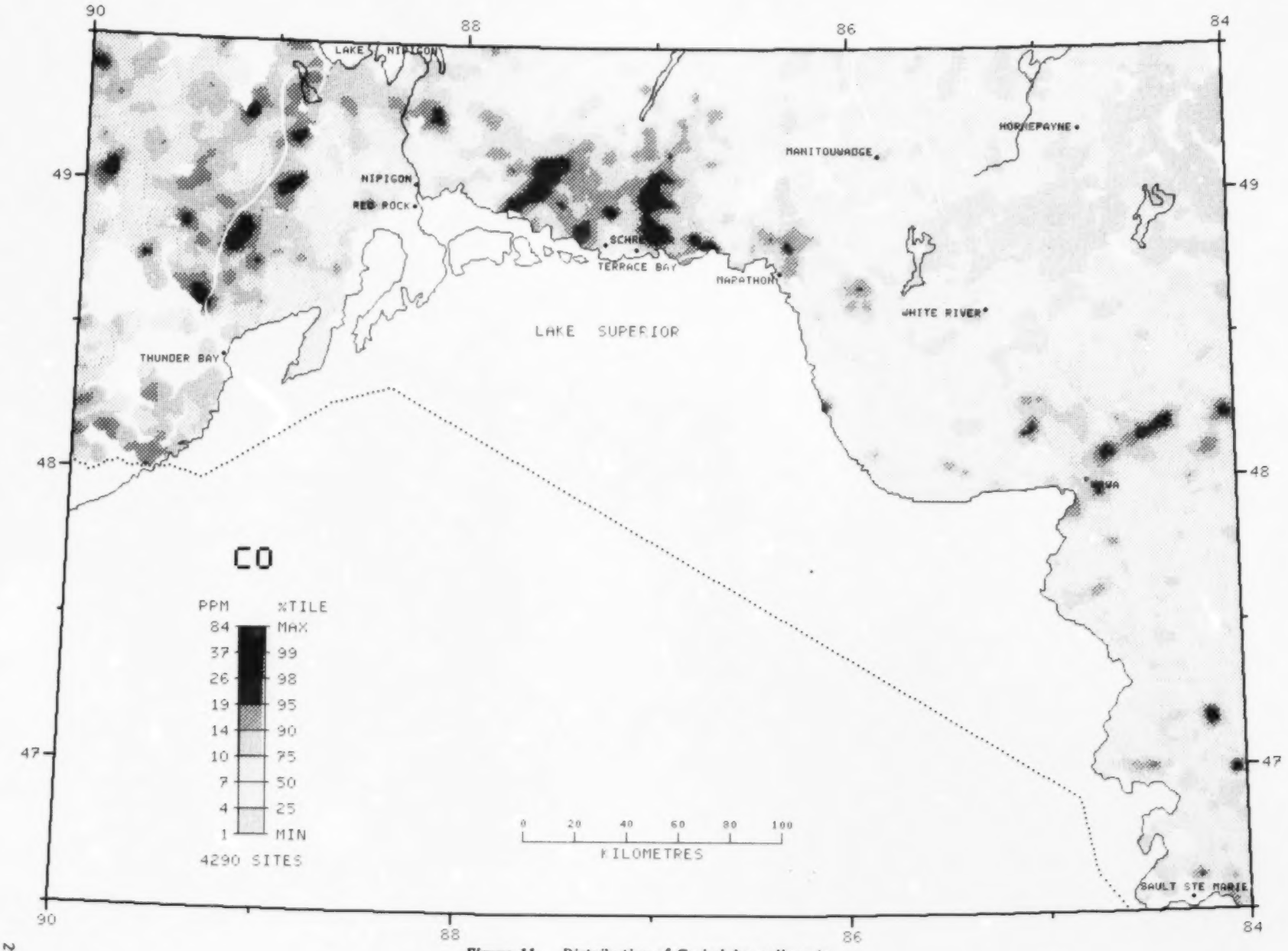

Figure 11. *Distribution of Co in lake sediments.*

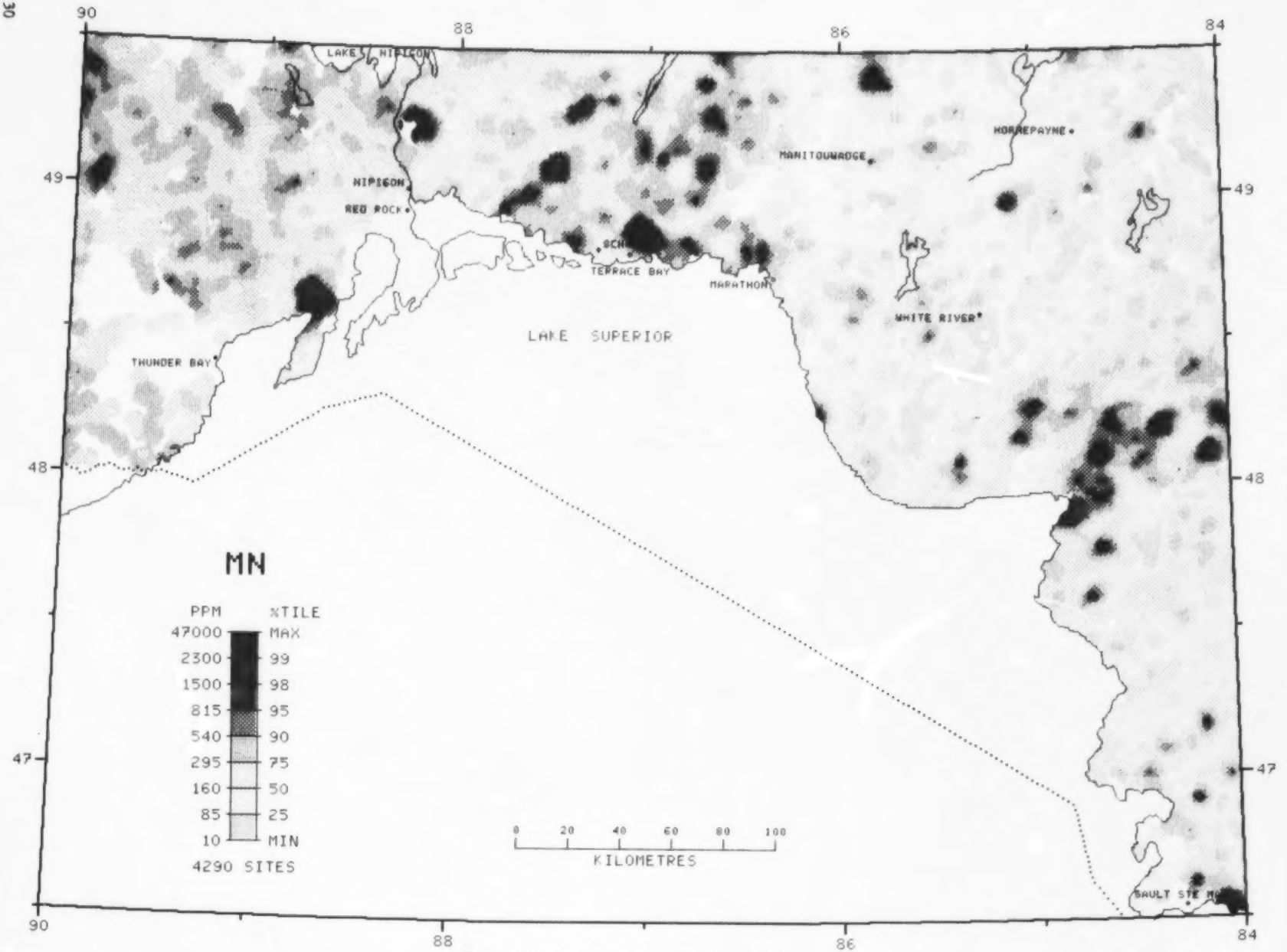

Figure 12. Distribution of Mn in lake sediments.

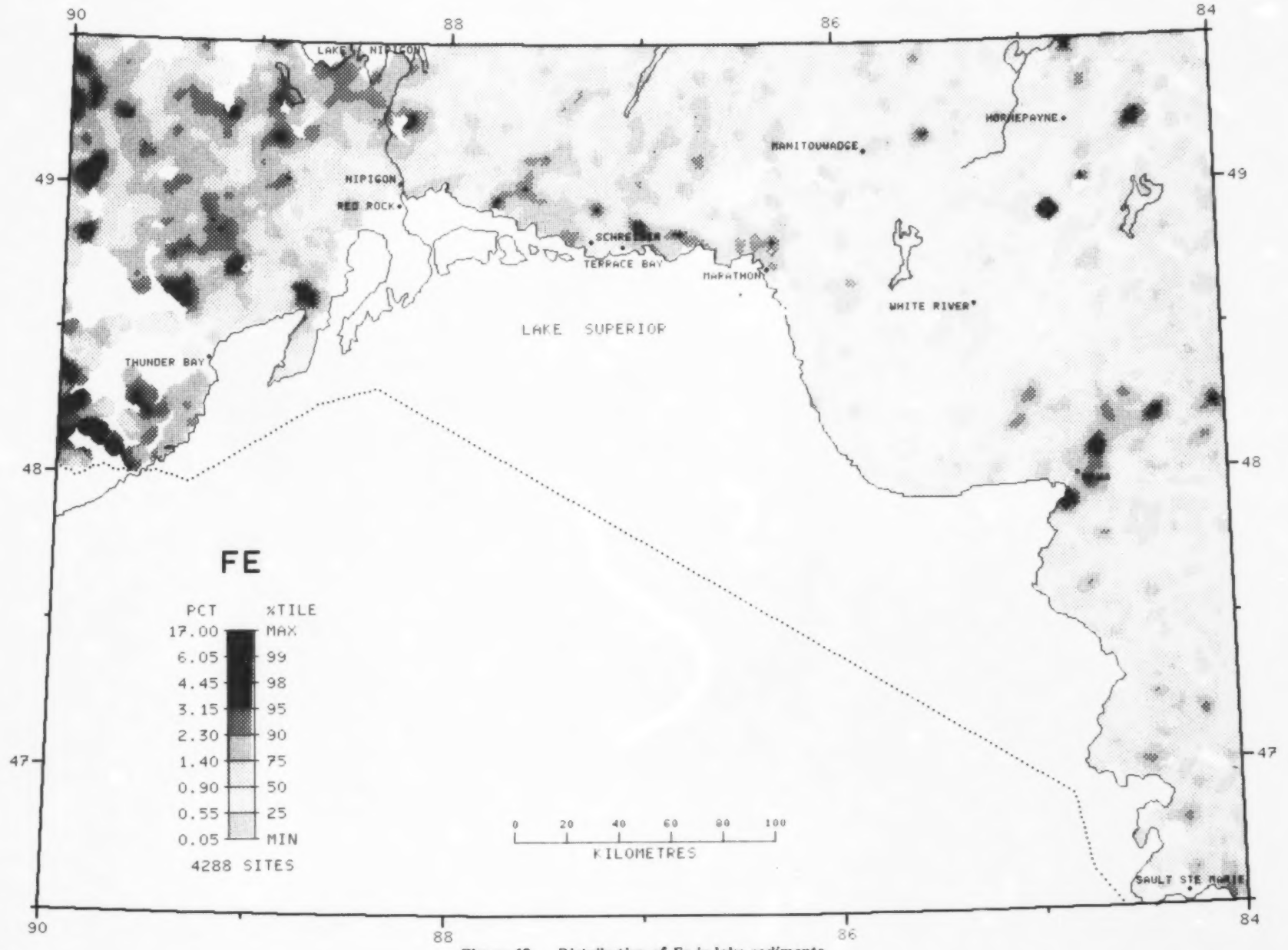

Figure 13. *Distribution of Fe in lake sediments.*

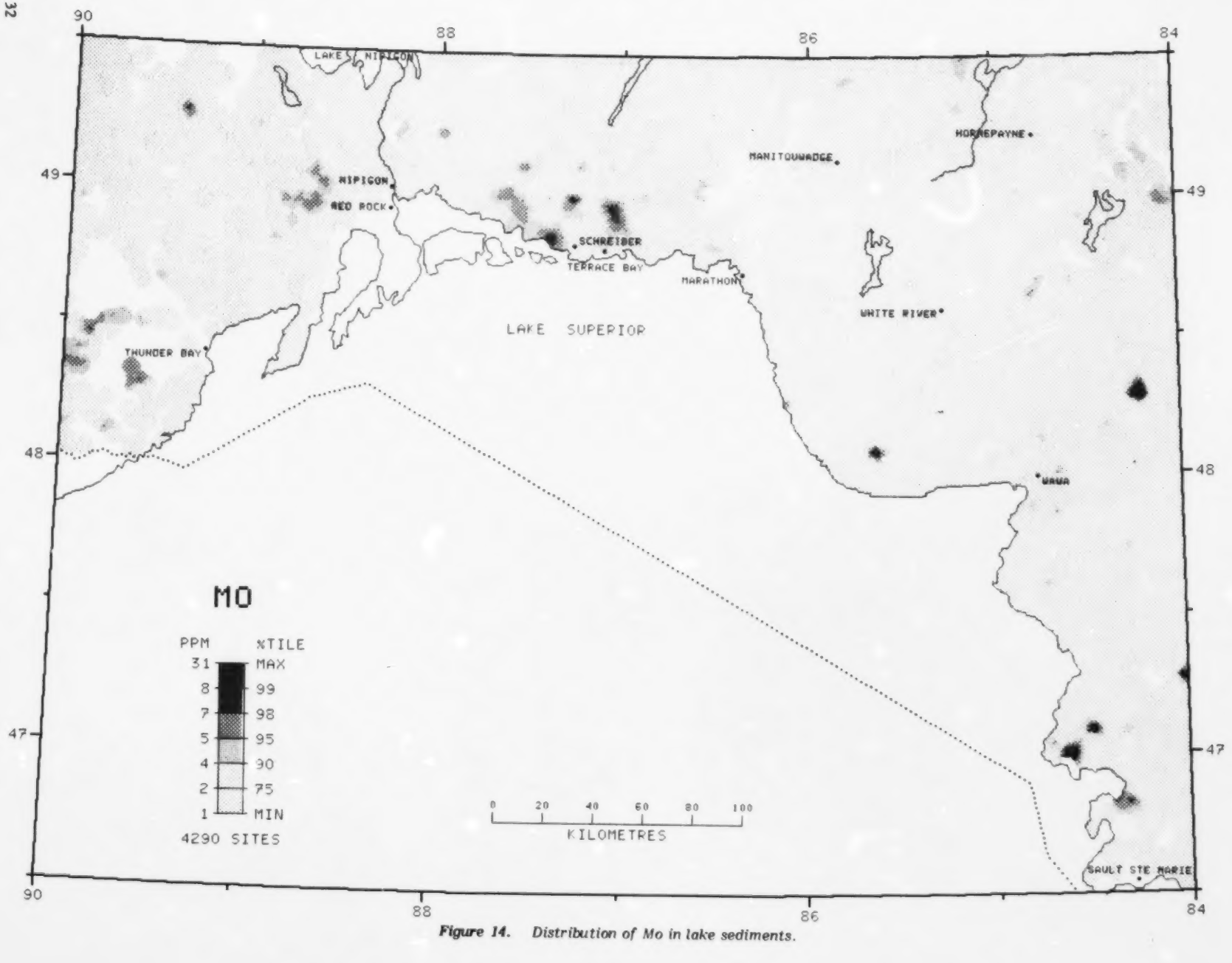

Figure 14. *Distribution of Mo in lake sediments.*

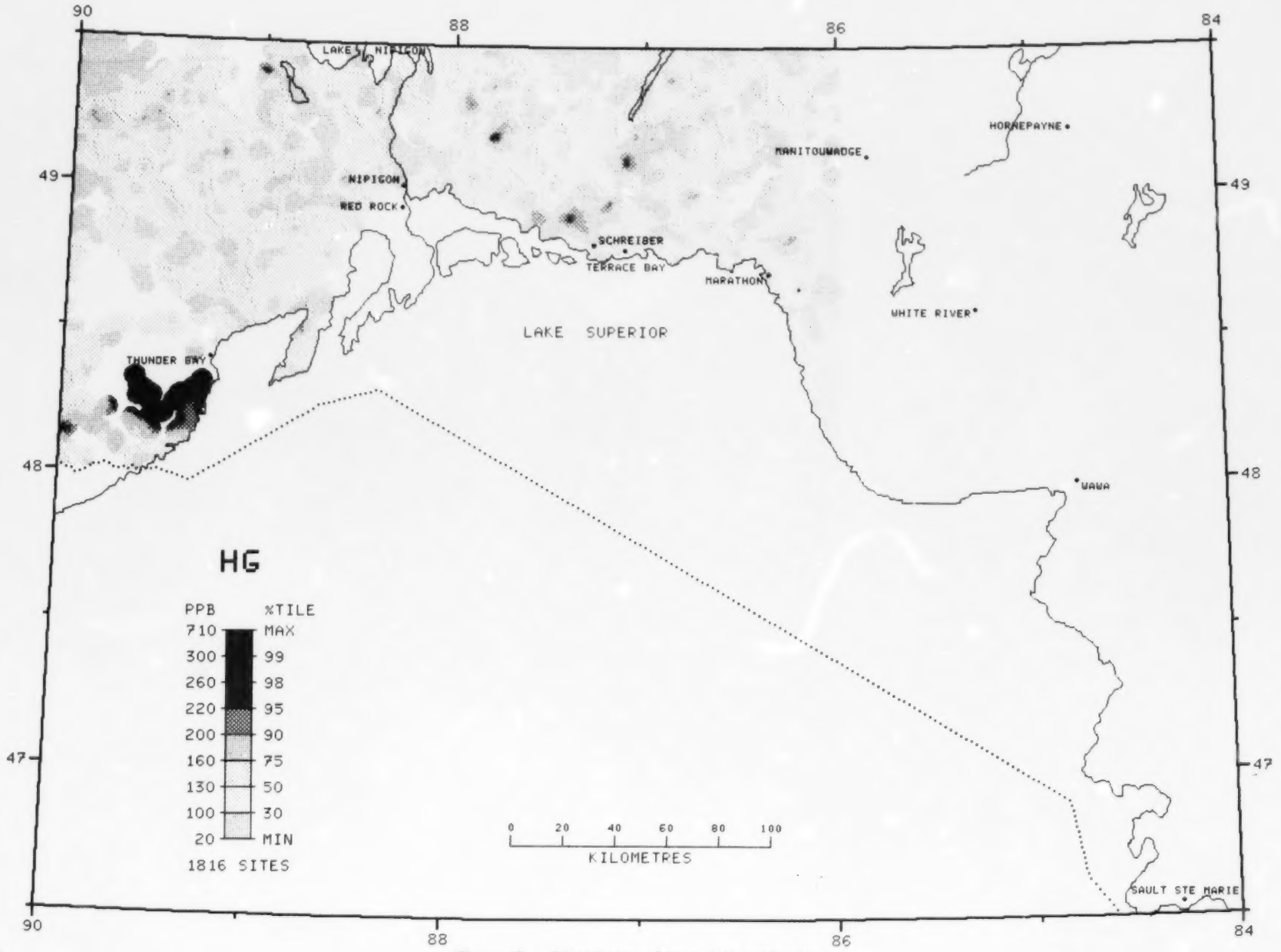

Figure 15. *Distribution of Hg in lake sediments.*

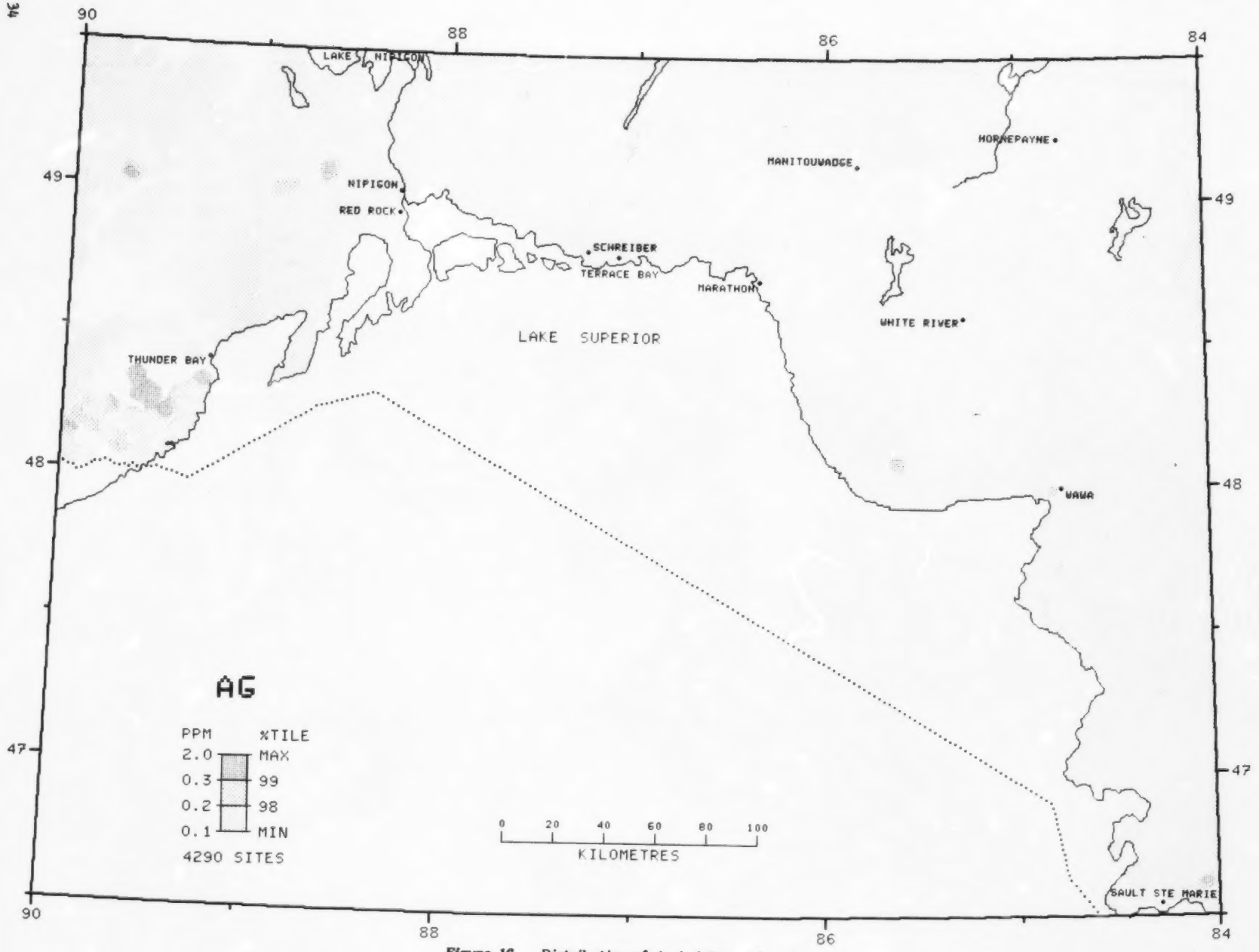

Figure 16. *Distribution of Ag in lake sediments.*

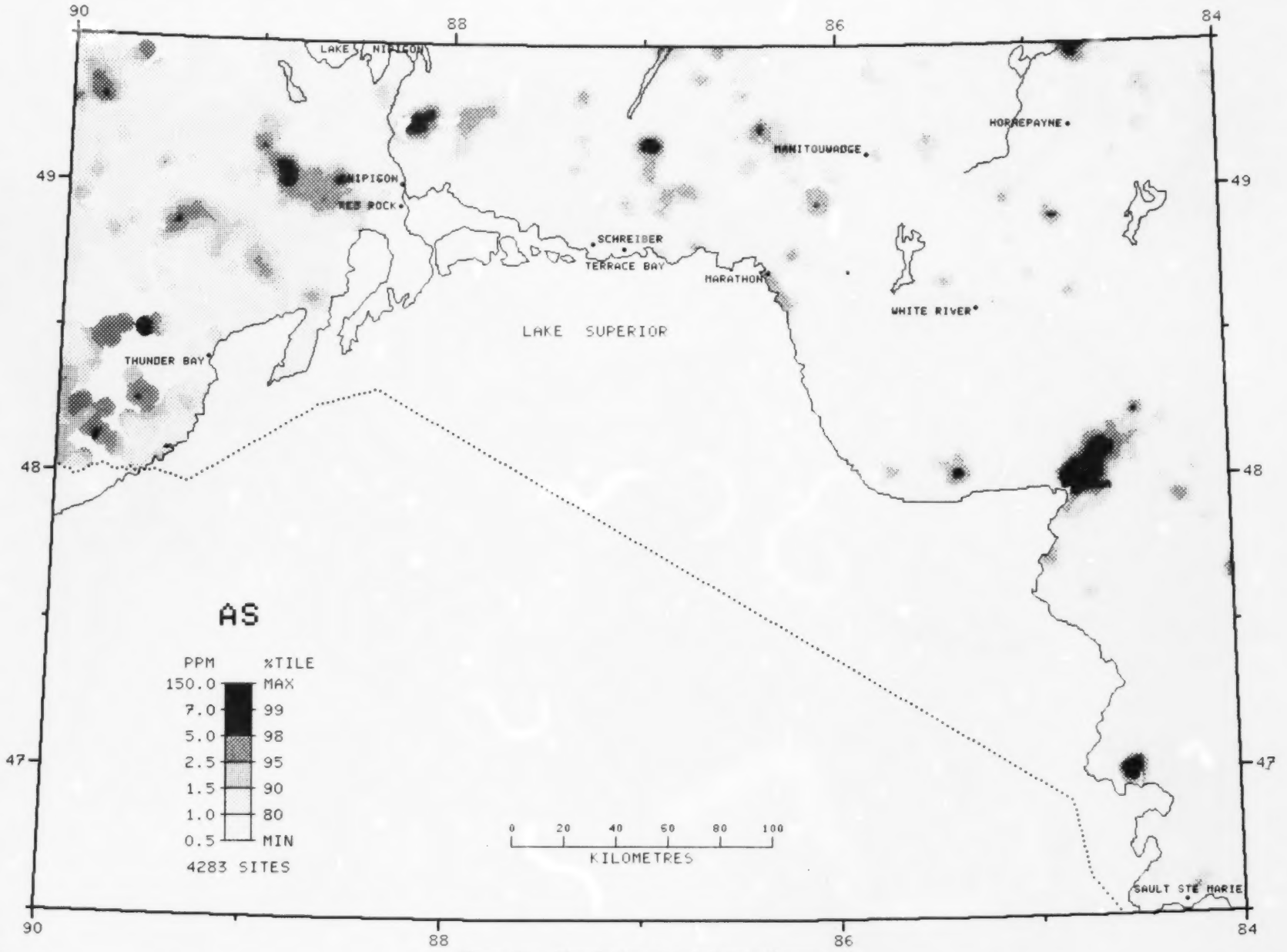

Figure 17. *Distribution of As in lake sediments.*

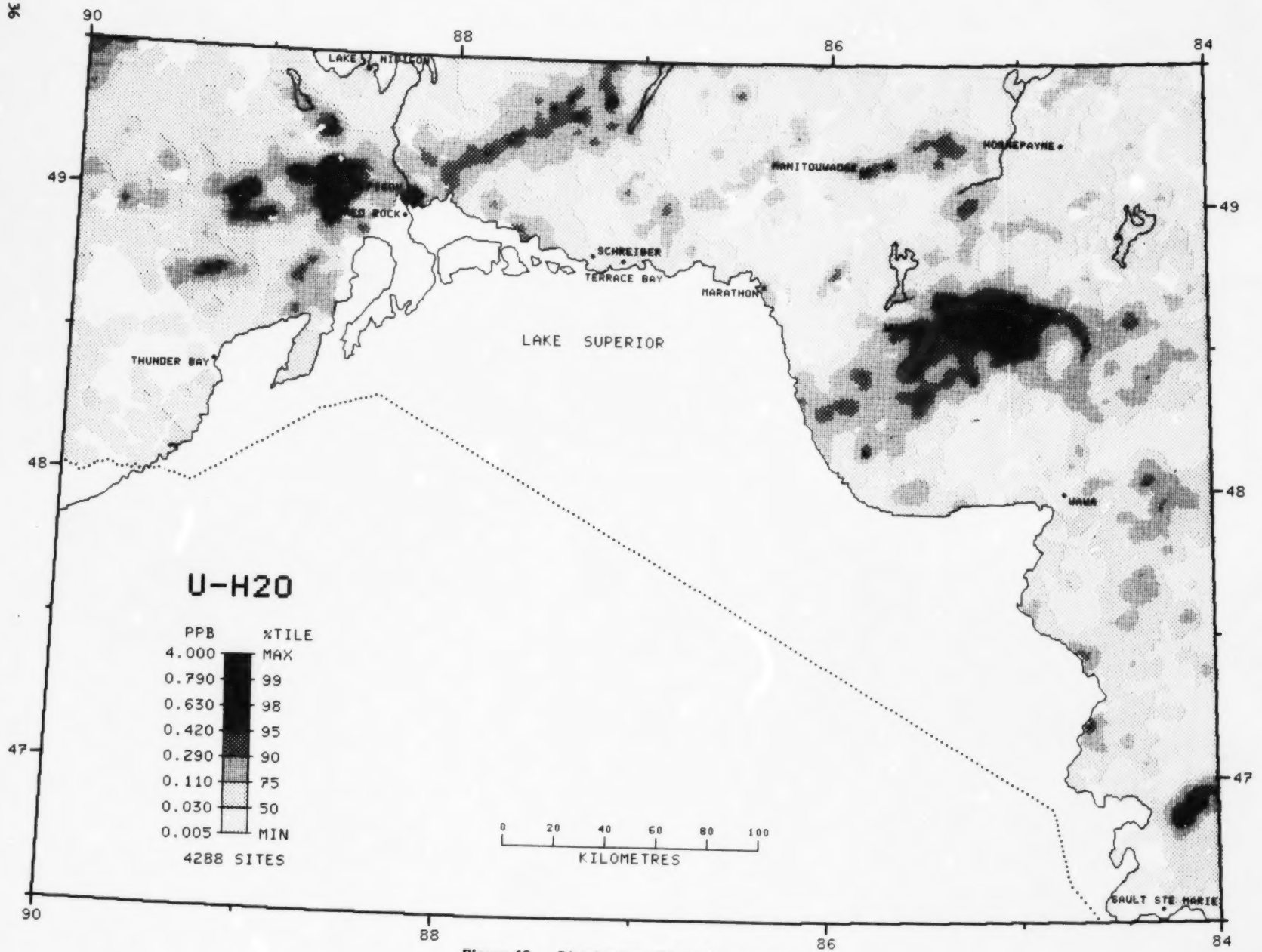

Figure 18. *Distribution of U in lake waters.*

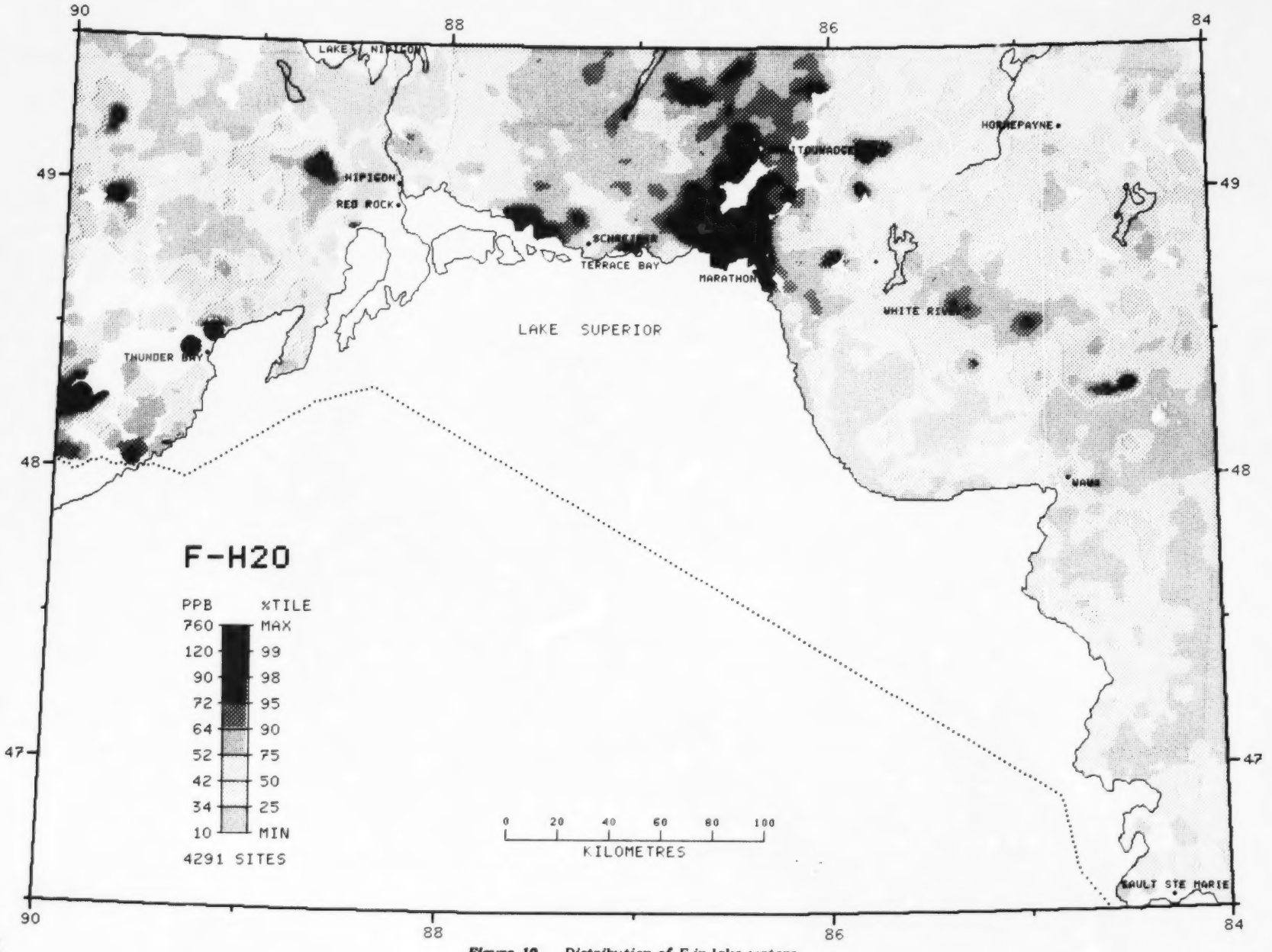

Figure 19. *Distribution of F in lake waters.*

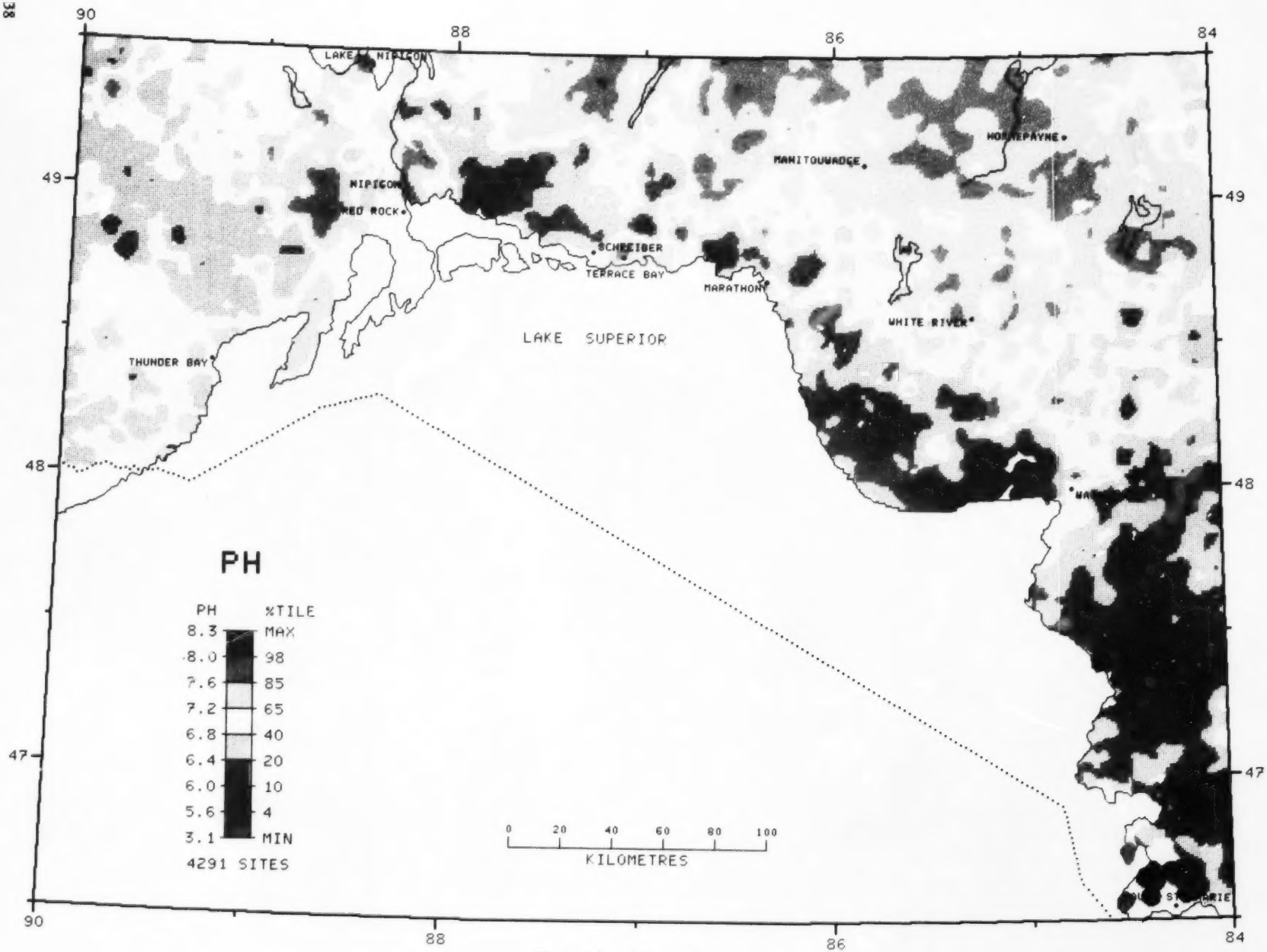

Figure 20. *Lake water pH.*